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Fine Surface Finish

FINE SURFACE FINISH

for designers, draughtsmen, engineers, inspectors, mechanics and engineering students

by

SYDNEY F. PAGE
M.I.B.C.A.M., M.M.I.A., A.M.I.E.D.

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Author's Note

The author wishes to express his thanks to those technicians, engineers and industrial firms who have so willingly placed information at his disposal, in the hope that others may benefit from their technical knowledge:—

Mr. P. T. Hollingan, D.F.C. B.Sc.; Mr. C. Timms, M.Eng., A.M.I.Mech.E.; Mr. F. E. Jearum, M.I.B.E., M.I.P.E.; British Precision Diamond Tools Ltd.; Messrs. Carborundum Co. Ltd.; Messrs. Commer Cars. Ltd.; Messrs. Churchill Machine Tool Co. Ltd.; Messrs. English Steel Corporation Ltd.; Messrs. Fletcher Miller & Co. Ltd.; Messrs. Glacier Metal Co. Ltd.; Messrs. Hayward Tyler & Co, Ltd.; Messrs. Pitter Gauge & Precision Tool Co. Ltd.; Messrs. Skefco Ball Bearing Co. Ltd.; Messrs. Taylor, Taylor and Hobson Ltd.; Messrs. A. C. Wickman Ltd.; The National Physical Laboratory; The Controller, Machine Tool Control; The Publishers of *The Automobile Engineer*; The Publishers of *Machinery*; United Steel Companies Ltd. Research Dept.; and to Mr. E. F. Johnson of Missouri, U.S.A.

Introduction

IN presenting this book the author has in mind the demand of designers, draughtsmen, engineers and engineering students, for concise facts on working surface finish. The facts presented form only the beginning of the subject, and after compiling the information, it becomes increasingly clear that every section could contain additional information if the subject were to be dealt with completely; this information therefore can only form a basis for the reader to practice and develop.

Engineers are constantly seeking new methods of improving their products, and this is a matter of great importance now when engineering products are required for use after a long war which has caused such a shortage of new equipment.

Legions of new applications of scientific principles have been introduced and used in mechanical weapons of war, and one of the sciences which has been applied to practical work is that pertaining to surface finish on the working parts of machinery.

If statements may appear in this book contrary to those held by readers, thus provoking thought and prompting constructive opposition, the author will feel that progress has been made.

Since 1938 an entirely new conception of surface quality and finish has been brought about in the sphere of machine working parts, especially in the field of internal combustion engines. This is largely due to the introduction of scientific surface measurement meters which enable the height of surface irregularities on working surfaces to be held uniformly to less than five micro-inches by finishing operations.

The practical methods quoted are the results obtained during the war industrial period 1939-1944, when industry mastered the art of cutting metals on a large scale, and the book is written in the hope that their use will assist engineers, especially if they are concerned with quantity production.

The significance of this at once suggests the careful study and utilization of new processing equipment and also introduces new and more accurate data on which to study the wear of working parts, as well as the readjustment of bearing clearances in internal combustion engines.

The use of correct types of bearings and suitable lubrication is one factor (SECTION 2).

Wear of metal surfaces is dependent on many factors, and it must always be borne in mind that the composition as well as the treatment of the material used has to be considered (SECTION 3).

This leads to considerations of machining methods and surface producing processess (SECTIONS 4, 5 and 6), while the methods employed in ensuring uniformity of a given surface demanded by the work it will be called upon to do (SECTION 7).

The diagram (FIG. 1) illustrates methods of processing a piece of stock to a fine surface component. One important

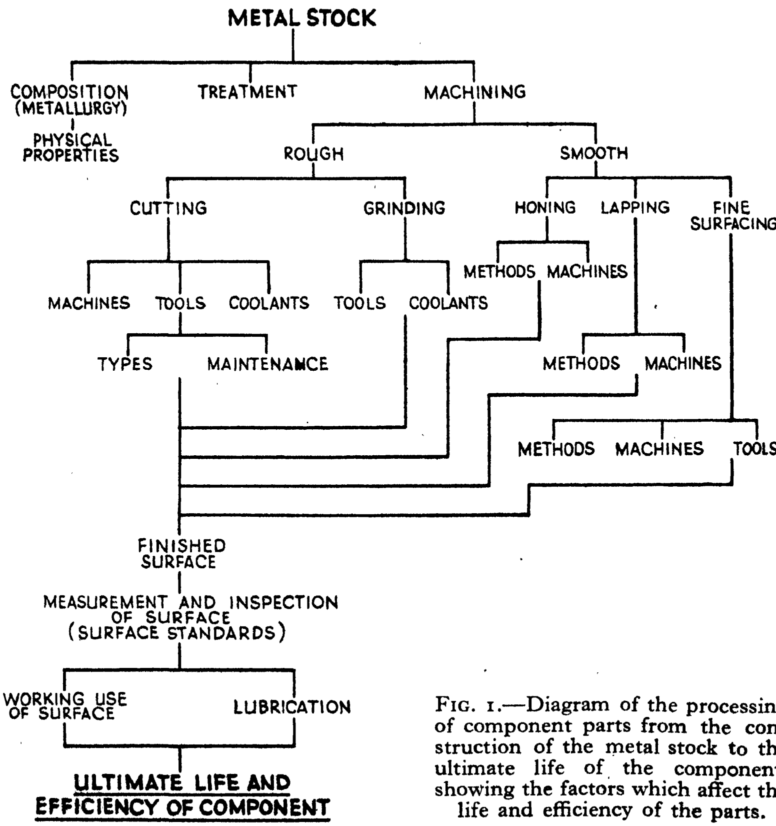


FIG. 1.—Diagram of the processing of component parts from the construction of the metal stock to the ultimate life of the component, showing the factors which affect the life and efficiency of the parts.

link in the chain of component production is inspection, and this is covered by SECTION 8.

In introducing the subject of research in SECTION 9, the author has by no means lost sight of the practical side, but aspects of a practical nature, especially cutting speeds and feeds, are so closely linked with research that, in order to ensure continuity, research must be considered in the light of its relation to modern metal machining.

SECTION ONE

The Reasons for a Controlled Surface Finish

SCIENTIFIC method concerns itself with the approach by successive stages of ever increasing refinement, nearer to exactitude, and in view of the increasing interest shown by engineers in the field of suitable surfaces for high speed working parts in modern machinery, the practical application of methods demands careful and systematic study by those whose job it is to produce satisfactory surfaces, in order to obtain refinement.

Throughout the engineering world many far reaching improvements have been brought into practical use due to consideration of the quality of working surfaces.

The demand for surface finishing among certain branches of engineering, such as machine tools, automobile, motor ships and aircraft, has led to information being made available, much of this information being of a technical nature.

Running surfaces of all kinds which go to make the motive power of transport and other undertakings have been the subject of considerable research, especially of the war years 1939-1945.

To define a surface as having length and breadth but no depth, is of little value to the engineer because it remains only a definition—not a practical description. The description must include the shape and character of a surface in addition to the size.

Friction

Since friction is of paramount importance to the smooth and efficient working of any machine and the length of useful life, it is of importance that the reduction of friction should be accomplished by carefully considered methods according to the work demanded of the two mating surfaces.

Bearings form one of the major parts of any machine and reduction of friction in these bearings may be accomplished by various means, such as the use of anti-friction metal and lubrication by suitable oils and grease, but the cause of friction is by no means removed.

One result of numerous experiments indicates that the condition or character of the surfaces in respect of roughness has a vital bearing on the reduction of friction to manageable proportions.

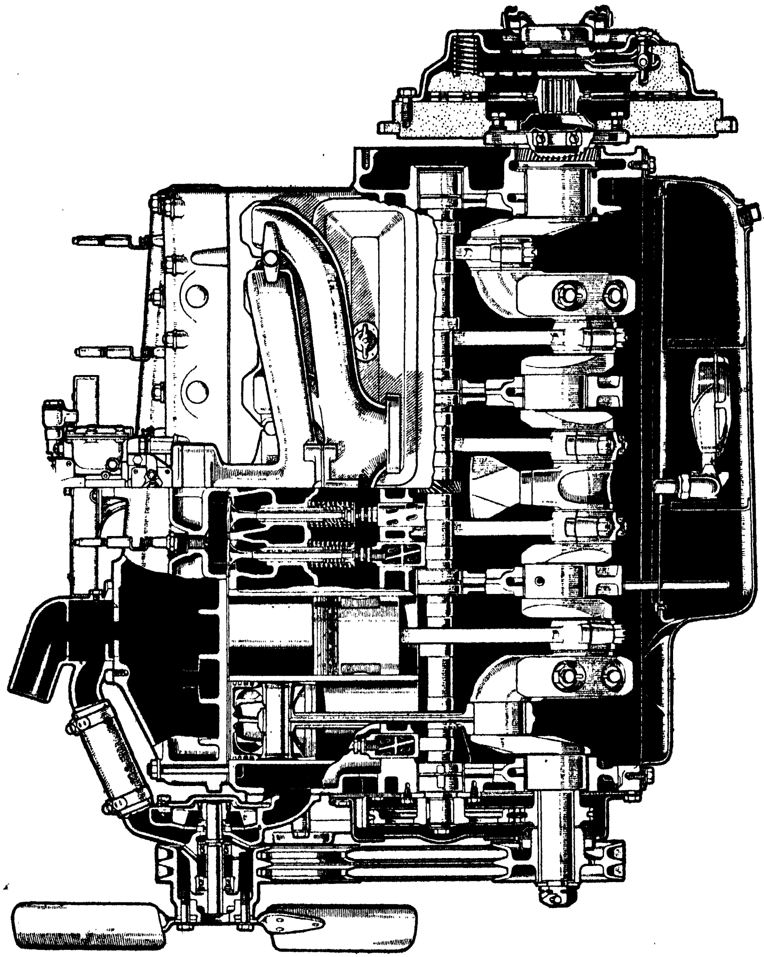


FIG. 2.—Section of engine.

The importance and relationship of the types of wear are discussed in SECTION 2, but it will be understood that any finish on the surface of metals which reduces metal-to-metal contact is of the greatest value.

Automobile Engines

In the field of engineering design, and especially in the motor industry, there have been researches which have led to the use of fine surface finishing as a separate operation after the component parts have been given their shape and size; such additional operation being applied to crankshafts, camshafts, gudgeon pins, pistons, valves and valve guides, cylinder bores, bearings and tappets.

Engine production and design has been so co-ordinated that production management has been able to take full advantage of quantity production on a scale previously unknown.

Consider some of the high spots of production.

Cylinders

In machining quantities of cylinder blocks using carbide tipped tools, such machine tools have been designed to rough and finish mill at one setting. Drilling, spotfacing, semi-finish and finish reaming of holes have been carried out progressively as the cylinder block is moved from one station to the next, such a co-ordination of operations eliminating the handling of heavy parts from one individual machine to another.

Care to obtain a suitable finish to cylinder bores has demanded honing methods and machines which have a combined control of boring and honing to produce bores within tolerances of .0005 in. for taper and out-of-roundness.

One firm of heavy commercial vehicle manufacturers has a standard surface finish for bores set at a maximum of 20 micro-inches.

Crankshafts

Crankshaft journals are produced by rough-grinding, drilling as required, milling as required, straightening, balancing and finishing with a machine lapping operation producing a surface finish of 10 micro-inches maximum.

Gear Manufacture

The most modern practice has been utilized in gear production, such practice consisting of rough and finish hobbing, followed by shaving on rotating shaving machines. Gears are lapped in sets or pairs.

To ensure correct heat treatment, each batch of steel has a sample set of gears made throughout in the ordinary manufacturing methods, and inspection enables corrections and adjustments to be made to the processes before the steel actually goes into quantity production.

Aircraft Engines

Prior to 1938 it was frequently stated that the manufacturing of aircraft engines could not be carried out successfully by quantity production methods largely because of the high degree of accuracy and finish demanded. Yet by scientific application of methods and machines, the employment of high production equipment, constant research and a high quality of inspection, such quantity production has been carried out on a scale thought impossible.

The use of vertical turning and boring mills on crankcases as well as turret lathes, ensure such close dimensional limits that accuracy of assembly is ensured to a large extent. Cutting tools which include many specially designed types have made considerable use of carbide tips and inserted blades.

During the manufacture of crankshafts one example of tolerances allowable is shown by the fact that 10 splines gauged by precision methods had only a permitted tolerance of .0008 in.

Automatic machining of aircraft components has reached a high standard of precision and accuracy due in the main to the fact that the labour available was of an unskilled or partly skilled nature. Automatic machines which only required loading and unloading by the operator have taken high place in the machine shops.

An example of this type of machine drills twenty holes, reamed and counter sunk, the parts being loading at the first station, and ten $\frac{29}{64}$ in. diameter holes drilled at the second station. Ten more holes are drilled at the third station. Combined reaming and countersinking is carried out at the fourth and fifth stations.

Such operations were previously performed on a number of independent machines and it has been proved in this one case that the use of the one automatic machine has cut production time by 70 per cent.

Throughout the whole vast undertaking of mechanical production for war runs the factor of inspection and checking, which comprise all the points of standardization, dimensional accuracy, finish and so on. This is of such importance that SECTION 8 has been compiled from experiences and information available from a number of different sources, both in Britain and America.

The inspection has been carried out by the use of precision made gauges, which must have a particularly fine finish and maintain a high degree of accuracy. Plug, taper, truncated, thread, surface, plate, optical, and a host of special types of gauges have been produced in large quantities. The standard by which these gauges have been accurately maintained are known as gauge blocks, and both these blocks and gauges are discussed fully in SECTION 8.

Machine Tools.

Machine tools have had the advantage of increased efficiency by the application of fine surface finishes to the many revolving and reciprocating motions employed, especially in the construction of such parts as high-speed grinding spindles.

The cutting edges of tools have their life prolonged by careful attention to the sharpening and finishing of the tool, and this important question is discussed fully in SECTION 9.

Before studying surface finishes it will be sound practice to consider the meanings of terms which are inseparable from this branch of engineering.

Nomenclature.

Abrasive Speed.—The linear speed of an abrasive stone in relation to the work speed.

Amorphous Metal.—Often considered as the binding material for crystals in the structure of metal, but is not crystalline and has no determined form. The smear metal on the surface of a component caused by the shearing action of a cutting tool during operation.

Base Metal is the crystalline surface exposed by the removal of the smear metal.

Crystalline Metal.—The basic form of most metal construction used in engineering, such crystals being in shape and bound together with amorphous metal.

Dimensional Finish.—The accuracy which is demanded by the fitting together of two parts implies a good surface with dimensional accuracy.

Fragmentation.—The crushing of the crystalline structure during the cutting or shearing action of a tool causes fragmented metal on the surface of a workpiece.

Micro-inch.—It is first necessary to obtain a standard by which surface comparisons may be made, and the method of expressing such a standard and all measurements relating thereto is based on the micro-inch (·000001in. = one millionth of an inch). The surface quality is recorded in micro-inches and the lower the number of micro-inches the finer the surface.

Metal Structure.—Most metals take the form of a crystalline construction which is formed during the cooling after melting. These crystals grow until they are stopped by adjoining crystals, and material of a different type, known as amorphous, binds the crystals together.

Physical Properties.

Brittleness.—The property of breaking without warning, or without visual deformation.

Ductility.—The property of being permanently deformed by tension without rupture.

Elasticity.—The ability to resume original form after the removal of the force which has produced a change in form.

Elastic Limit.—The greatest unit stress that the metal is capable of withstanding without permanent deformation.

Factor of Safety.—The ratio of the ultimate strength to its working stress.

Flow or Creep.—The gradual continuous distortion of metal under a continued load.

Impact Strength.—Force in foot-lbs. required to break the metal when applied with a sudden blow.

Plasticity.—The property of being deformed under the action of force and not returning to its original shape upon the removal of the force.

Strain.—Distortion set up by the action of an external force.

Stress.—Internal forces set up by the action of an external force.

Surface Micro or Roughness.—Irregularities comprising minute peaks and valleys covering the surface. Especially after the metal base has been processed by one of the machining methods.

Surface Macro or Waviness.—Irregularities on the surface in which the height is far greater than the depth.

Bearing Area.—The amount of actual load-carrying surface on a working component which is in effect a percentage of the total surface area.

Co-efficient of Linear Expansion.—This is the change of the linear dimensions of metal parts for each degree of temperature change.

Oxidization.—A state of the metal surface produced by atmospheric or other natural causes.

Scratch Pitch.—The distance between scratches shown on a profile of a surface.

Scratch Depth.—The depth of a scratch varying according to the type of machining operations.

Relation of Factors to Ultimate Finish.

In recent years the introduction of manufacturing processes under the headings of plastics and powder metallurgy have brought about new methods in the construction of some types of component parts. But machining units in various forms is still considered as the most important method of production, and demands for more efficient forms of machining have, in turn, required precise information on the actual cutting operations.

Opportunities to sort out the leading questions and find answers to them have been plentiful during the past years and the motor industry, in particular, can justly claim leadership in many of the improvements in engineering which have resulted in increased and more efficient life of machines. As an example, engine horse-power per pound of weight has been developed from one horse-power per 350 lb. to approximately one horse-power per 1 lb.

Side by side with the development of engines has been the development of machine tools for the production of components which form the working part of the engine, such working parts being machined to very close limits.

Vibration, one of the main causes of slow speeds and ultimate breakdown, especially in reciprocating parts, has been greatly reduced by the scientific balancing of such parts carried out during the machining processes.

Improvements in manufacturing include the ability to cut hard and tough metal at increased speed, while the use of jigs tools, fixtures and gauges make interchangeability a simple process.

Fine surfacing finishing after machining operations, to ensure dimensional accuracy, contributes to the ultimate efficiency of the machine.

Dealing with these three important factors in order, the ability to cut harder and tougher metals at increased speed has resulted in more rigid and heavier constructions of machine tools to eliminate chatter, and this, in turn, has led to the use of sturdier and more satisfactory cutting tools.

Machine tools have been designed for high-speed production, and this has brought about various methods ensuring that the

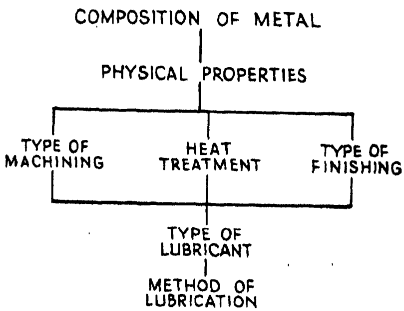


FIG. 3.—Table of factors effecting component wear.

component parts are similar in every detail. Jigs, fixtures and gauges are used for holding each component during the machining operations, thus ensuring a definite degree of accuracy being maintained regardless of the size of the component.

As to the actual surface, the development of finish has been considered as a science, especially during the War years 1939-1945, largely because of the many factors which enter into the production and application of working surfaces in relation to the vast quantity of machines produced demanding a high degree of interchangeability of component parts. This has enabled answers to be obtained to important questions, such as:

Can a required surface finish be correctly specified?

Can a definite surface specification be demanded by a customer?

What value can a designer place on the finish of components in his machine?

Can a specification be used by the inspection and production departments?

The above are but a few of the types of questions which are asked, but they indicate the importance of recognizing surface finish.

The strength of working parts which have to withstand strain demands good surface finish, as may be seen by such highly stressed parts as those in modern aircraft engines, railway locomotive and carriage axles, such components demanding the best of surfaces in order to function efficiently.

The study of surface finish in this book is planned progressively and takes the following order:

Types of wear and lubricated surfaces.
Metallurgy of machined surfaces.
Machining of surfaces.
Grinding methods.
Finishing operation of surface finish.
Inspection.
Research.

Reasons for careful finishing may be summarized as follows: Longer life. Improved efficiency. Less power required for driving. Reduction of vibration, giving increased comfort. Lower cost of the articles to the buying public. Fewer repairs and replacements. Easier and more accurate replacements, when required.

The importance must be considered in all branches of engineering: refrigerator, vacuum cleaners, electric motor, stationary engines, railway rolling stock, and locomotives, marine engines, diesel and internal combustion engines, machine tools, power drives, clutches, trains of gears, power stations, steam engines, turbines, and other branches too numerous to list.

It must not be considered, however, that the production of a high quality surface is the cure for all the problems of wear, because the factors of dimensional and geometrical accuracy enter largely into the reduction of wear, but practical fine finish on working surfaces, obtained by scientific methods, has far-reaching results on the ultimate life and working efficiency of such surfaces.

Every working surface produces results which affect the following six major factors, and by scientific control of the finish, produces increased efficiency in all these factors: (1) Load-carrying capacity; (2) Reduction of friction between lubricated surfaces; (3) Relative strength of the parts; (4) Control of surface quality; (5) Reduction of corrosive action on the surface; (6) Inspection of quality and dimensions of the parts.

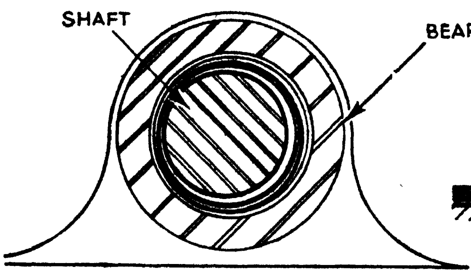
SECTION TWO

Comparisons of Lubricated Surfaces

VERY many new methods to improve the lubrication of bearing surfaces have been tried, especially during the past four years. To realize how many of these methods will assist the user of machines and motor vehicles it is necessary to study the principles of the lubrication of running surfaces—the reasons for lubrication and the method of application.

Hydrodynamic Principle

The basis for understanding this principle is to consider the requirements of the lubricant. The most important characteristic is its viscosity, as a frictionless fluid cannot sustain a load



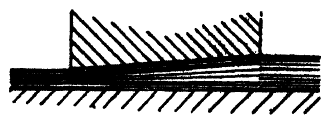


FIG. 4.—Hydrodynamic principle. FIG. 5.—Wedge action.

Reynold's theory of the oil wedge. This theory of lubrication is based on the adhesive and cohesive action of the oil. The oil adheres to the surface of the bearing and shaft, and during the shaft rotation the oil viscosity creates fluid pressure which supports the load thus preventing metal-to-metal contact.

such as is required to keep a revolving shaft from the bearing. When two surfaces are separated by oil, a thin layer of oil will adhere to both surfaces and as the successive layers of oil move with velocities, which decrease as the distance between the surfaces increase, shearing action must take place between adjacent layers of the fluid; thus if one surface is inclined as in FIG. 5, the wedging action takes place which builds up pressure between the surfaces, as will be seen in the diagram FIG. 4, in which it will be seen that the oil cushion and wedge as applied to a shaft and bearing, if maintained, will do much to prevent metal-to-metal friction. Fundamentally the problems involved are dominated by the two complementary factors of friction and lubrication, since one of the primary reasons for lubrication is to reduce the formation of friction.

The finish of the surface has a marked effect on the results obtained in the researches made into the field of friction and it has been proved that high friction on comparatively rough surfaces is in a large measure due to the interlocking of the surface irregularities.

We have already seen that friction between moving parts forms one of the basic factors affecting the design of those parts, so that the force and importance of friction must be considered and methods of analysing and overcoming it must be scientific.

Since most books on applied mechanics devote some chapters to the various types of friction, it will not be necessary to repeat formulae in much detail here, but one elementary law, that of the co-efficient of friction, must be considered.

Where $N =$ Normal force between the surfaces;
$F =$ Friction force;
$u =$ co-efficient of friction, then $u = \frac{F}{N}$

and this is most easily proved in FIGS. 6 and 7, where a block weighing 20 lb. N on a surface with a force of 4 lb. F just moves the block across the table. The co-efficient of friction in this case is $\frac{4}{20} = \cdot 2$.

If we lubricate the surface between the sliding block and the table it may be found that a much lighter force will be required to move the 20 lb. block, and the co-efficient will be correspondingly less.

From the above simple illustration it is clear that a number of factors enter into the final make-up of the co-efficient of friction. These include the method of lubrication, the type of lubricant as well as the type and material of the bearing surfaces, while the total bearing area of the surface and the speed of running must also be considered.

Regarding the method of lubrication, this may be divided into (*a*) boundary lubrication, and (*b*) true fluid lubrication. Boundary lubrication means that the rubbing surfaces are not in direct contact, but are separated by a very thin layer of lubricant.

The friction, however, is still influenced by the characteristics of the surfaces, and under these conditions some abrasion of the surfaces occurs.

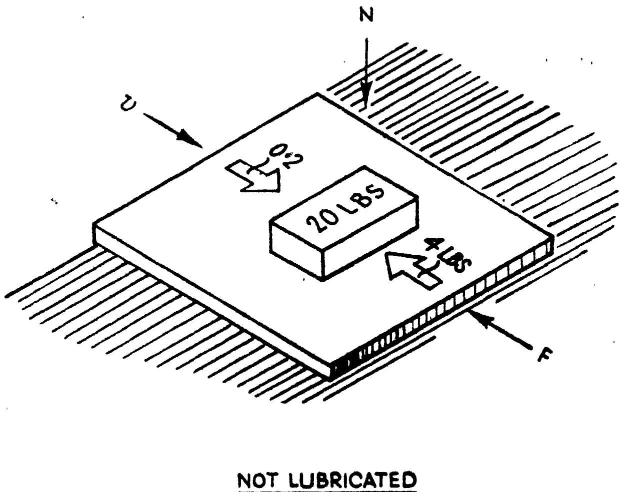


FIG. 6.—A 20 lb. block sliding on a non-lubricated surface and requiring 4 lb. pull to move it. u = co-efficient of friction = ·2.

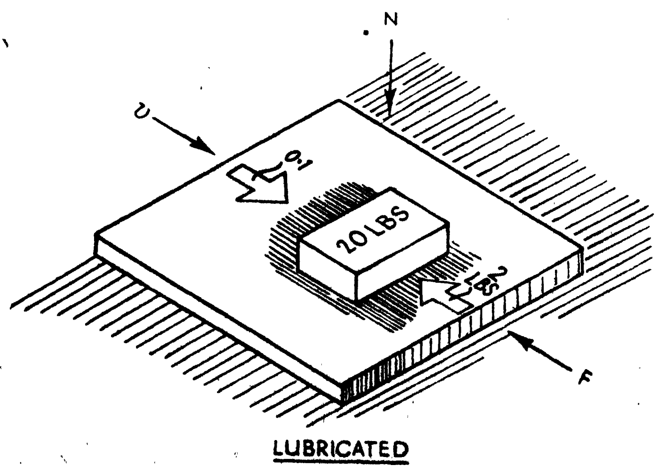


FIG. 7.—The same block sliding on a lubricated surface. u = co-efficient of friction = ·1.

The viscosity of the lubricant does not affect the friction, but it does determine the influence of the load.

True fluid friction, as may be seen by studying the hydrodynamic principle, is quite different in as much as the surfaces are separated by a fluid layer so that the direct influence of the surfaces disappears and any friction created is due to the viscosity of the fluid.

Heat generated in bearings under conditions of boundary lubrication gives rise to temperatures up to 550°C., but these temperatures are not consistent, being in effect a series of steps which tend to prove the theory that surfaces weld together momentarily at the point of contact, followed by a sudden slip which introduces fluctuations in both friction and surface temperatures.

It follows that if the clearance between shaft and bearing is insufficient, local overheating will occur due to metal-to-metal contact, with a resulting failure in either the shaft or the bearing. The maximum clearance between bearing and shaft varies with the diametral clearance and the lubricant viscosity, being the square of the diametral clearance and the square root of the lubricant viscosity.

Factors which concern the lubricant include freedom from foreign matter and particles of metal. In the case of an internal combustion engine the danger stage is during the running-in period when the minute particles of fragmented metal are being removed from the various running parts. These tend to circulate within the oiling system, and are frequently the primary cause of scored bearing surfaces.

While it would no doubt be interesting to consider in greater detail the types of friction, the production of lubricants and oil films, and the theory of the bearing surfaces setting up electro-magnetic forces, it is the practical control of friction with which we are mainly concerned, and so this SECTION will deal largely with the moving parts of motor car engines (see FIG. 2) and machine tool surfaces.

Probably the two working parts of any engine which have had the greatest amount of attention paid to them are the pistons and cylinder walls, and these will be considered first.

Tests made into the causes of wear in pistons, piston rings and cylinder bores have brought about some very enlightening results. The basis of these tests was the plotting of wear over 10,000 miles at an average of 2,500 ft. per mile of piston travel.

One of the points proved was that an oil film must be maintained at all times between the working surfaces; and this leads to the fact that cylinder wear falls into three broad headings: (1) Abrasive (2) Erosive, and (3) Corrosive.

Abrasive wear is largely attributed to the intake of particles of dust during the piston suction stroke.

Erosion or "scuffing" is caused when the piston breaks through the oil film with the resulting metal-to-metal contact of piston and cylinder wall surfaces.

Corrosion is set up during the initial starting of the engine, when the very thin film of oil is washed away by the condensed petrol which is used to assist the ease of firing when the engine is cold. This process of washing away leaves the bright cylinder walls free to be attacked by corrosive agents until the oil has circulated and can once more form a supporting film on the surfaces.

One factor which demands that the oil film be maintained is that the piston warms up much quicker than the cylinder bore by reason of the greater bulk of metal around the cylinder and the water surrounding the cylinders. The difference in the type of metal used for the construction of both piston and cylinder also affects the oil film because, as the piston expands during warming up, the clearance between piston and cylinder wall decreases. Such expansion tends towards the easy rupture of the oil film, and the consequent metal-to-metal contact which must take place, is often part of the so-called "running in" of new motor vehicle engines. But in fact it is the removal of peak metal which in turn causes increased clearance between the running parts.

In a test made to determine the amount of "running in" required before an engine could be considered efficient, the following procedure was adopted:

The bore of a well-known make of engine was honed with 400 grit stones to what was considered a good finish. Conventional piston and rings were inserted, and the engine brought up to working temperature. It was run for one hour at 3,650 r.p.m. and then stripped down, showing a severe wear on the pistons and rings. Without touching the bore in any way, a further piston and set of rings were installed and the test repeated. Severe wear of the running parts was again prevalent. This procedure was carried out six times before the mating parts could be considered as relatively free from wear.

Thus it may be seen that the removal of the fragmented layer of metal from the sides of the cylinder walls is of primary importance to the maintenance of an oil film.

It will be remembered by all who have purchased a new motor vehicle in the past that such a purchase is a signal for the start of a strict "running in" period, if excessive wear is to be avoided at the start of the life of the vehicle. Why is such care necessary?

FIG. 8 makes this clear. It is a sketch of a piston inside a cylinder, the surface of both having been finished by ordinary

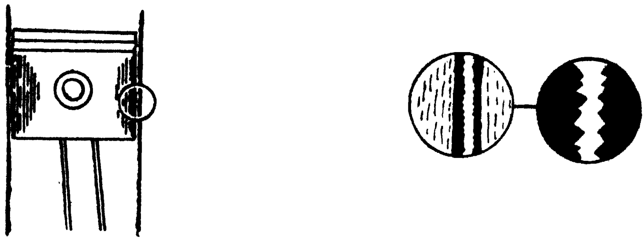


FIG. 8.—Sketch of piston and cylinder, showing peaks left by the machining processes, which have to be dispelled during the "running in" period.

commercial methods, the piston by fine grinding and the cylinder by honing.

Reference to the surface records in SECTION 6 shows the profile of surfaces which may be expected from these commercial

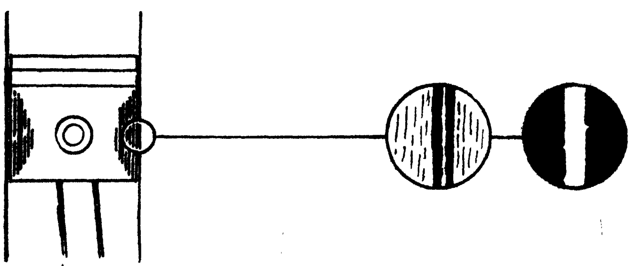


FIG. 9.—Sketch showing the value of surface finishing piston and cylinder bore. Note the oil pockets below the maximum bearing surface. These pockets ensure the adhesion of oil to the working surfaces.

processes. It will readily be seen that despite the oil film which is present between the surfaces, the movement of the parts against each other allows metal-to-metal contact where the machining process leaves a series of metal peaks higher than the base metal. Such peaks cause a rupture of the oil film, which in turn melts these peaks, and wearing on one or both surfaces follows.

After the "running in" period, which actually amounts to the wearing down of these peaks to the actual bearing area (say for the first 500 miles of running) the clearance between piston and cylinder increases.

This suggests the fact that the problem of the wear, which has so serious an effect on the engine, has to be ultilized for producing a suitable finish to each working surface before the machine will function efficiently. But it is doubtful whether

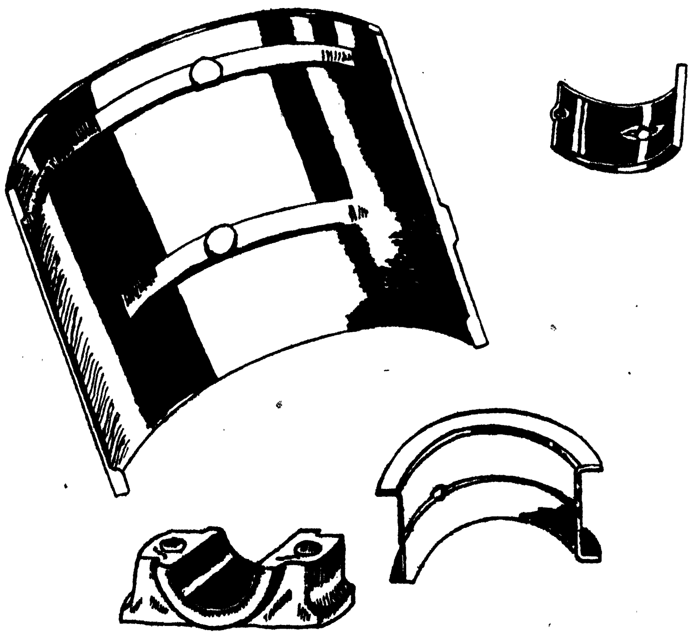


FIG. 10.—Types of "white metal" engine bearing.

the problem of wear will conveniently adapt itself so as to disappear as soon as those surfaces have been produced. In fact, each rupture of the oil film gives rise to minute welding of chips, thereby setting up heat and reproducing the whole process again.

Another pair of working surfaces which so often give rise to trouble are the big-end bearings and shafts. There are a number of types of bearings, some of which are shown in FIG. 10.

The schematic layout of a bearing with the oil film and journal is shown in FIG. 11.

This figure also shows a journal which has been surface finished.

It is evident that future bearing developments will be toward a very thin lining of tin or lead base alloy metal, backed by steel. To enable these very thin linings to function accurately it will be necessary to ensure that they are not subjected to contact with the steel journal by reason of fragmented metal on the journal surface.

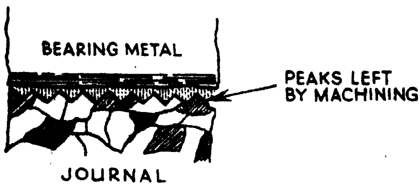


FIG. 11 (a).—A section of big end illustrating the metal-to-metal contact under load due to the oil film being ruptured.

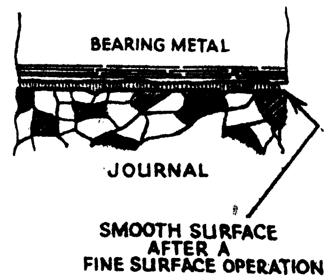


FIG. 11 (b).—A section of a big end illustrating the smooth oil film which is required to carry the load.

We may, therefore, summarize wear as the removal of material from surfaces in contact with each other, one or both of which are moving, while dirt and abrasive foreign matter circulating in the oiling system also play their part in wearing away the surface. Another point is the corrosion of certain types of steel by a reaction formed when high temperature oil absorbs oxygen. Fatigue of the metal with consequent flaking of the suface must also be considered, especially in the case of a scored bearing.

Fluid Friction

Most lubrication of surfaces may be considered as being accomplished by fluid friction, which is inherent in lubricating oils as well as other fluids having any appreciable viscosity.

To understand the true meaning of the word "viscosity" we must consider the fluid as being made up of molecules which are held together by a force known as molecular attraction. This force causes a resistance to motion of one molecule to another. The effect of this resistance to motion is the viscosity of the fluid. The viscosity of lubricating oil is also influenced by temperature, as may be observed when cranking an engine by hand on a cold morning. High internal friction of the fluid causes the oil to flow sluggishly, but as the oil warms up and becomes lighter in viscosity it circulates freely.

During operation under high temperatures some oils tend to become too thin to support the working stresses, or they may decompose, forming a sticky substance known as "sludge," which collects on valves, valve springs and in the bottom of the sump, as well as in the oil-feed pipes.

Oil Lubrication

The following is a description of practical oil lubrication and it will be seen that it is applicable to all types of surface which use the fluid film lubrication.

If a piece of smooth metal has been well oiled, and is treated with a solvent to remove the oil, the surface will appear to be completely free from oil. By applying water to this surface, however, the resulting running off of the water leaves the surface dry. This is due to the oil, which has been absorbed into the structure of the metal, forming a film which the solvent fails to remove. It is this ability of the molecules to orient themselves on a metal surface which enables oil to cling to the surfaces and thus support the load properly. In the case of a rough surface, the molecules adhere to the peaks and fill the valleys of the scratches, but those on the peaks will have no supporting molecules and the film will easily break down as pressure is applied.

On the smooth surface the molecules will be supported by each other, and it is thus impossible for them to be separated or swept aside when the pressure is applied.

A turbulent action of the fluid is set up in a rough surface and when the oil is sheared in an irregular line, the result is excessive fluid friction with a resulting local rise in the temperature of the lubricant.

Descriptive sketches of oil at work on a rough and smooth surface are shown in FIGS. 12 and 13.

In FIG. 12 a number of molecules adhere in some part to the two surfaces, but the disturbances of the central molecules may also be observed. By comparison, FIG. 13 illustrates the well-ordered layer of molecules, which not only adhere to the surfaces of the metal, but maintain cohesion with those adjoining.

Shearing of the oil occurs in an orderly manner, and the film carries the load without undue rise in temperature.

Modern high-speed machining increases the functions of lubricating oils, and in consequence the properties of satisfactory oils cover a wide and varied range. They must be free from

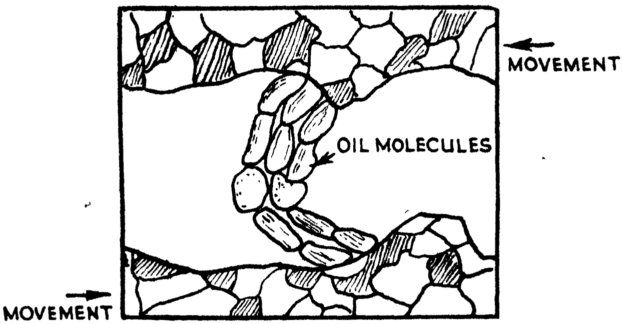


FIG. 12.—Oil at work between two rough surfaces. The creation of turbulence in these conditions causes high fluid friction, and increased temperatures, leading to a rupture of the oil film.

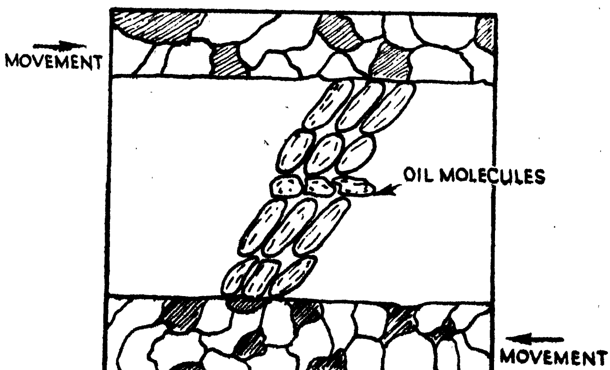


FIG. 13.—Oil at work between two smooth surfaces. The easy shearing action between the molecules, with freedom from turbulence is clearly seen.

ingredients which form sludge, while at the same time provide proper cooling and be able to carry away the heat developed by fluid friction. But they must maintain sufficient strength to carry the load of pressures applied in shear and maintain a high film strength.

Viscosity of a lubricant, its load-carrying capacity, resistance to shear and film strength, have all proved to be related to the chemical nature of the lubricant, a definite chemical reaction between the lubricant and the metallic surfaces under load being required.

Heat generated within the engine by reason of its working parts must be readily dispelled by the oil, as engine bearings must be kept below 200 °C. to ensure satisfactory running and life.

Pistons reach temperatures of up to 1,080 °C. at the explosion or power stroke and they must be kept sufficiently cool to prevent melting. The principal functions of a lubricant may be summarized as follows:

(1) Cooling (2) Lubricating (3) Sealing (4) Scavenging.

With the foregoing information on lubrication and oil films, engine lubrication as well as lubrication for other forms of machinery may be considered. When finishing the component parts of a machine by the commercial machining operations a certain amount of smear metal is present on the working surfaces.

The assembly of these working surfaces calls for very close limits in fitting to ensure smooth running with silence.

The peaks above the main bearing area of the surface allow conditions of pressure until these peaks are worn down.

But there are no conditions in which either the amount of wear can be controlled, or the rate at which wear takes place, so that during the whole life of the machine there is a continuous lubrication problem. The fact that the rough surface peaks do wear down is an indication that the lubricating oil film has been pierced, causing an instantaneous rise in local temperature, thus breaking or melting these metal peaks.

During this breakdown, minute scoring takes place and by a gradual process the limits between the fitted parts increase and demand lubricants with a heavier viscosity to fill the gap so created.

From this point a pounding action takes place as the components are subjected to working pressures, and the higher viscosity demanded to counteract this condition will increase the fluid friction, and create sluggish movements of the sliding components.

It may, therefore, be seen that it is first desirable to finish the sliding and working parts so that there are no surface peaks, rather than that the maximum bearing surface should be obtained before the initial fitting of the parts.

The question of maximum bearing surface is governed by several factors and does not imply a surface finish which is absolutely free of any indentations. While it is clear that peaks above the maximum bearing surface are undesirable, some method must be used to ensure that a quantity of the molecules of oil will adhere to the bearing surfaces and so assist in supporting the load and a smooth shearing action.

This may be accomplished by minute scratches below the bearing surface. But care must be observed because, if the limits of the two mating surfaces are closed and the oil film thin, and since the oil film equals the load between the surfaces, it will tend to take the line of least resistance and flow out of the bearing surfaces, and if the scratches are large enough they will assist it to do this.

FIGS. 12 and 13 show the action of a film of oil while two bearing surfaces are working.

Summarizing, if a machining operation is performed to produce the surface intended as a working surface, and then the fragmented layer is removed by a fine surfacing process, the resulting surface has a maximum bearing surface, and at the same time minute scratches are left below the surface to act as reservoirs and minimise any area which has a tendency to seizure.

Ball and Roller Bearings

Over a period of years strides have been made in the production and application of ball and roller bearings, and the modern types may be relied upon to give long and satisfactory service, providing that correct types are used in accordance with the principle laid down by the manufacturers.

The following notes on the subject of lubricants and lubrication of these types of bearings have been supplied by the Skefco Ball Bearing Company Limited in their publication *Installation and Maintenance:*

> There is a fundamental difference between the use of oil and grease for the lubrication of ball and roller bearings. A suitable grade of oil can provide a suitable lubrication, but frequent renewal is necessary unless there is a large oil sump with a sealing device so effective as to prevent leakage, or unless a suitable and efficient circulatory system is employed.

On the other hand a suitable grease may be relied on to serve its purpose for long periods, does not require elaborate housing design, is economical, and constitutes an excellent means of protection against rust and the entry of foreign matter.

As a rule grease requires adding to or renewing no more than once or twice a year.

Oils

When, owing to the prevailing conditions of speed or temperature or to other circumstances, the use of oil is essential, only straight mineral oil may be used. Oils of animal or vegetable origin, even though they may have good lubricating qualities, must be avoided owing to the risk of their becoming resinous or of the formation of acids that attend their uses. The controlling factor in the selection of a ball bearing oil for a given application is viscosity. Light oils (low viscosity) are suitable for small and medium bearings under light loads, and at high speeds; medium oil for medium and large bearings running under normal conditions, and heavy oils for large bearings subjected to heavy loads.

Greases

The melting point of the grease used must be much higher than the working temperatures. Approved greases may be divided into two classes: cup grease compounded from lime soap, and sponge grease componded from soda soap. Lime soap greases melt at about 90°C., but since they soften and decompose at lower temperatures than this, the maximum working temperature should not as a rule exceed about 45°C. Such greases must not be melted to facilitate their application to the bearings since they disintegrate on melting and do not return to their original conditions on cooling. Soda soap greases are characterized by having a very tenacious and clinging nature. They readily emulsify with water, and this property makes them suitable for application where small quantities of water are apt to find their way into the bearing housing. These grades are suitable for a wide temperature range extending usually for 20°C. (minus 4°F.) to 90°C. (194°F.) If good quality soda soap greases melt under the influence of too high a temperature, they will regain their original consistency after cooling.

With regard to the change in the temperature of the balls or rollers and their races during working, the following notes from the same publication will be found of value:

Speeds that are high for the size of the bearing used, or heavy loads, cause a certain rise in temperatures.

Normally, both the rings of the bearing run at about the same temperature, and the diametric slackness remains constant. If, however, conditions are such that the inner ring becomes hotter than the outer ring, the intitial slackness will be diminished.

Excessive temperatures also tend to reduce the carrying capacity of a bearing, and consequently, its life.

Comprehensive experimental investigations on the life of a bearing have proved that the carrying capacity cannot be determined by means of theoretical calculations alone, owing to the complex nature of the conditions set up between the bearing elements as a result of the elastic deformation that occurs when two bodies with curved surface come into contact with each other. Recourse must therefore be made to the results of tests and practical experience.

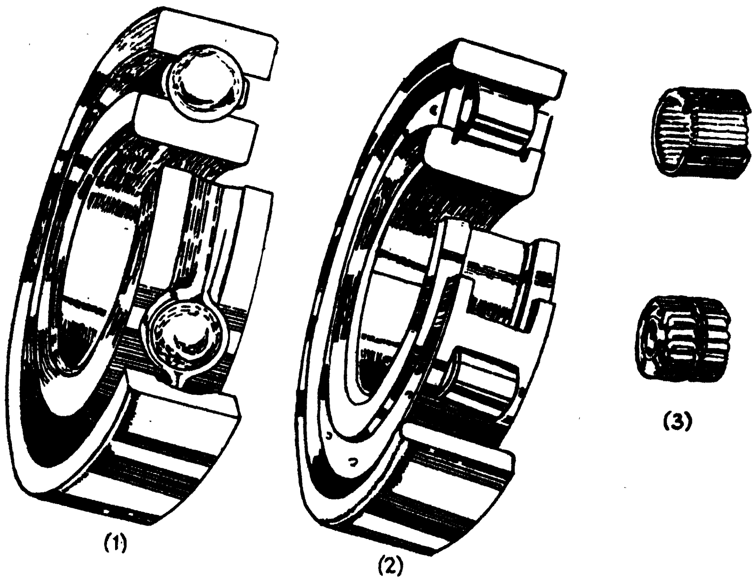


FIG. 14.—Some types of rolling bearings.

(1) Single row ball. (2) Single row roller. (3) Needle bearings.

From the foregoing notes it will be seen that great care and precision are required in the manufacture of ball and roller bearings, and it follows that the working surfaces of the inner and outer rings must possess a high degree of finish, which in turn demands careful selection, machining and treatment during manufacture, and constant inspection of the metals used is of the greatest importance. FIG. 14 shows a number of the standard types of ball and roller races which covers a wide range of sizes and load carrying capacities.

Engine Bearings.

The following notes are reproduced by permission of the publishers of *The Automobile Engineer*, and are extracted from an article entitled "Engine Bearings", by W. D. B. Brown, P. T. Holligan, D.F.C., B.Sc., and J. W. Warrington:—

Recent Research on Friction

Dr. Bowden and his co-workers at Cambridge, have, in work carried out from 1935 onwards, established certain important fundamentals. Their work has shown that the kinetic friction between unlubricated surfaces is independent of the load, of the apparent contact area and of the surface velocity. It has also shown that the materials of the rubbing contacts exert an influence. Moreover, it has been established that the frictional effect is not confined to the surface layer of the metal, but causes distortion and abrasion to an appreciable depth below the surface. The effect of surface finish has also been investigated, and with the materials under investigation it was found that surface roughness affects the result. In general, it was concluded that the increase of friction with very rough surfaces was due to the inter-locking effect of surface irregularities.

Of much greater interest to the bearing user is the behaviour of bearing surfaces under conditions of boundary lubrication and true fluid friction. Under boundary lubrication conditions the rubbing surfaces are not in direct contact, but are separated by a very thin layer of some material, usually the lubricant; but the friction under these conditions is still influenced by the characteristics of the underlying surfaces. Furthermore, under these conditions some abrasion of the surfaces always occurs. The viscosity of the lubricant does not affect the friction, but its nature does determine the influence of the load upon the friction.

With true fluid lubrication, the surfaces are separated by a fluid layer of appreciable thickness and the direct influence of the surfaces disappears. In this condition the friction is due to the viscosity of the fluid, and follows the laws of hydrodynamics. In practice, it may be considered that most bearings operate under conditions of boundary lubrication at times, and therefore the nature of the surfaces has a marked influence upon the frictional resistance.

Rubbing Surface Temperatures

Dr. Bowden's work has also thrown considerable light upon the surface temperatures that may be attained between rubbing surfaces. It has shown that with unlubricated surfaces very high temperatures may be reached in the order of 1,000°C., with high melting point metals. With low melting point metals the surface temperature reaches the melting point of the metal, although the mass of the metal remains cool. The temperature actually reached depends upon many factors and varies with the load, speed, kinetic friction and the thermal conductivity of the metals.

Under conditions of boundary lubrication temperatures of over 600°C. have been recorded. It was further shown that motion is not continuous, but consists of a series of slip-stick movements: that is, the surfaces weld together momentarily at points of contact and then slip suddenly occurs. These inter-movements are accompanied by violent fluctuations in friction and surface temperature. The time duration of the slip is exceedingly small, in the order of one-thousandth of a second.

Establishment of these facts is important, because they demonstrate that there may be momentary stresses and tempertures of much greater magnitude than those envisaged when motion was considered to be continuous. That these fundamentals have important reactions upon the practice of bearing design is apparent, but the factors involved are so numerous that every application must be considered on its own merits.

Two extremely important properties of bearing metals are "embeddability" and "conformability" each of these depends upon a combination of mechanical properties. "Embeddability" may be defined as the ability to engulf minute particles of foreign matter by local flow without causing local high spots and overheating of sufficient duration to affect the bearing. This property appears to demand low yield stress and ow hardness, and possibly low melting point. Hardness and yield point usually vary directly, and therefore the softer the metal the greater the degree of "embeddability". "Conformability" may be defined as the ability of the material at the bearing surface to yield under local pressure with a resultant uniform re-distribution of stress over the adjacent bearing surface area, thus eliminating local over-stressing and consequent failure. It would appear that high ductility is conducive to good "conformability", because it allows the metal to yield without cracking. Inaccuracies of alignment and surface finish, probably of a very low order of magnitude, are inevitably present in any commercially produced mechanism, and it is obviously important that a bearing surface should be capable of accommodating these inaccuracies without failure. Bearing metal hardness is also important from the point of view of the shaft material. This will be discussed later in this book.

It would, therefore, appear that a bearing material should possess the following, in some degree incompatible mechanical properties:

(a) Low co-efficient of friction.
(b) Low hardness for maximum " embeddability ".
(c) High ductility for maximum " conformability ".
(d) High compressive strength for maximum load carrying capacity.

Obviously, these properties cannot all be attained in any one metal, and therefore some degree of compromise is necessary or a mechanical solution of the problem must be sought. For any application consideration must be given to all relevant factors and the relative importance of the various desirable properties must be assessed. By this means it is possible to decide which bearing materials or combination of materials are best suited to any specific application. It will be appreciated that with the advance of design the problem of suitable bearing materials is becoming increasingly complex and can be solved only by the application of highly specialized knowledge.

Ultra-thin Linings and Tri-metal Bearings

One method of employing tin-base bearings for comparatively high loads is the use of bi-metal and tri-metal bearings with ultra-thin tin-base linings. It is well known that thin layers of metal will withstand deformation without cracking to a degree that would be impossible with thick layers. This is, of course, relevant to bearing applications, and the following theory would appear to apply:—

In the case of a member stressed in bending, the maximum stress will occur at the surface, and the stress will diminish progressively through the cross-section until it becomes zero at the neutral axis. With white metal linings of normal thickness, that is ·030 in. of white metal and ·050 in. in thickness of steel, the neutral axis will be situated in the steel shell and the whole section of the white metal will be subject to the maximum range of stress reversals which occur on reverse bending, that is, on flexure. The white metal must, therefore, withstand this range of stress without support.

With ultra-thin linings in the order of ·002 in., ·003 in., the surface is still subject to the maximum stress range, but immediately beneath this surface is a backing metal of steel, bronze or other strong metal. Because of this the ultra-thin lining forms only a very small fraction of the total stressed cross-section and, furthermore, it is supported by and can redistribute local high stresses to the stronger backing metal.

Two factors affect the bearings user:

(1) Bearing with ultra-thin linings cannot be reamed or scraped in any manner when they are fitted to the engine.

(2) Should an ultra-thin lining fail in service and run out the increase in clearence may not be sufficient to cause a definite knock to develop in the engine. Because of this, failure of an ultra-thin lining may possibly lead to a shaft fracture before the trouble is discovered.

This second possibility may be overcome by using a tri-metal bearing, that is, one which has a steel shell lined with a semi-soft bearing metal such as lead bronze, which in turn carries an ultra-thin Babbit lining. Obviously, if the white metal lining of such a bearing fails in service, although there will be a slightly increased oil clearance, the shaft will still be running on a good bearing metal.

Bearing Clearance

The provision of the correct bearing clearance is a matter of major importance, particularly in the case of high-speed engines. This fact is sometimes not fully realized by engineers who have previously dealt only with slow-speed engines. For any particular engine the correct clearance can be determined only by giving due consideration to the materials being used, to the dimensions of the bearings, and to their position in the engine, whether they are main bearing or big ends.

Too great a clearance can be a major source of trouble. It causes excessive pounding of the bearing due to the high inertia loadings obtained in high-speed engines, and also due to the loss of oil pressure. In addition, it may cause distortion of the shaft which in extreme cases may be of such magnitude that shaft fracture will eventually occur.

Inadequate clearance, which is generally found in bearings that have been hand fitted, can cause over-heating due to a breakdown of the oil film, and also to the restricted oil flow. It is generally conceded that at least eighty per cent. of the heat generated in a bearing is carried away by the lubricating oil. Because of this, it is essential that there should be a good flow of oil through the bearings. This condition cannot be met unless adequate clearance is provided. That bearing temperatures do rise rapidly with decrease in bearing clearance has been definitely established.

In general, oil flow through an engine bearing obeys laws approximating to those of viscous flow through an annular passage. In bearings of normal clearance the flow is directly proportional to the oil supply pressure and to the square of the diametral clearance up to clearances of about ·005 in. It is inversely proportional to the viscosity of the oil at the temperature of the bearing film and to the length of the bearing.

Oil flow increases rapidly with increasing speed of rotation, even although the oil intake temperature and supply pressure remain constant. This is due to the reduced film viscosity consequent on the increased operating temperature that results from increased speed. Individual design features, such as the type of oil grooving, location of bleed holes and end clearance, also influence oil flow.

As previously pointed out, if the clearance is insufficient, serious local overheating may occur, due to metal-to-metal contact and lack of heat dissipation. As a consequence, local failure of the bearing metal is possible. A fairly good guide as to the correct clearance to be used for white metal bearing with pressure lubrication, is clearance in the order of ·00075 in. per inch of bearing diameter. For copper lead bearings the clearance should be in the order of ·00125 in. per inch of bearing diameter. That this extra clearance for copper lead bearings is necessary has definitely been established in practice.

Fitting of Bearings

Present-day practice in automobile engineering is towards higher compression ratios and higher speeds, which impose increased loadings upon the bearings. Satisfactory performance under these conditions can only be secured if the bearing is correctly fitted. This is a point of major importance. Hand scraping of bearings is still widely carried out, but it is not considered a good method of fitting. A scraped bearing surface consists of numerous high spots, which make contact with the journal and prevent a proper oil flow during the running-in period. Owing to the lack of adequate oil flow, local heat is generated and the high spots soften until there is sufficient clearance to allow oil to flow freely through the bearing. Unfortunately, during the process of removing the high spots damage may be done which will result in bearing failure at a later date.

The depth of tool marks should probably be considered in terms of oil film thickness under pressure. If their height is less than the oil film thickness they will act as oil spreading channels. If it is greater, metal-to-metal contact will result, and in the case of white-metal bearings where the metal is soft, the high spots will be flattened out as a result of the heat generated and the consequent lack of hardness.

It is also of interest and importance to note that bearing manufacturers do not consider diametral measurement of the bearing to be a satisfactory method of checking a thin shell bearing for dimensional accuracy. The only thoroughly satisfactory method of determining this accurately is by measurements of circumferential length and wall thickness.

Length-diameter Ratio of a Bearing

Pressure per unit of projected area alone is not a complete criterion of the pressure an oil film will carry. In other words, two bearings of similar projected area, but having different length-diameter ratios, will exhibit differences in the maximum loads the oil films will carry without rupture. Consider the case of two bearings operating at the same rotational speeds, but having different diameters. The smaller diameter bearing will have the lower rubbing speed, and, other things being equal, the temperature rise in operation will be less. This fact may have an appreciable effect on bearing life, because of the temperature hardness characteristics of bearing metals.

A good reason for employing a high length-diameter ratio is not so obvious, but it is perhaps even more important. This may be made clear by consideration of two cases, one with a bearing of infinite length and the other with a very short bearing. In an infinitely long bearing have the clearance space filled with oil under pressure. It is reasonable to suggest that the pressure drop per unit distance will be considerably less than in a very short bearing owing to the greater distance from the point of maximum pressure to the ends of the bearing, that is, to the escape points.

Crankshafts in Relation to Bearings

That the inter-relationship of the crankshaft material and the bearing material is important and requires careful consideration both from the point of view of bearing life and crankshaft life, was demonstrated in the earlier remarks on friction. In practice, bearing life is affected by three factors concerning the crankshaft, namely, rigidity, surface hardness and surface finish.

Rigidity is a function of crankshaft design and is most important, because if shaft deflection occurs to a degree in excess of the conformability of the bearing material, high local loading will occur. This happens particularly at the ends of the bearing, that is, at the position of least mechanical support, and it may cause bearing failure. This trouble can be corrected only by re-design of the crankshaft, by stiffening the journals or webs or both.

Surface hardness of the shaft journal must be considered in relation to the bearing material in which it is to run. It is often a matter of compromise between performance and cost. In the case of white-metal bearings a soft shaft gives perfectly satisfactory results and the advantages to be derived from the use of a hardened shaft are not sufficient to warrant the expense of hardening. In general automobile practice crankshaft material is usually a medium carbon steel heat-treated to give a Brinell hardness of approximately 200. With such shafts white-metal-lined bearings must be used if excessive wear of the shaft is to be avoided.

When harder bearing materials are employed, soft shafts cannot be guaranteed to give satisfactory performance, although fairly soft shafts could be used with copper lead bearings if complete cleanliness of the oil is to be maintained. This is scarcely possible under commercial conditions. In practice, it has been found that shaft journals for use in conjunction with bearings other than the white-metal-lined type should have a Brinell hardness of not less han 300. It is of interest to record, however, that tests have been carried out using steel-backed copper-lead-lined bearings in conjunction with a shaft having a Brinell hardness of only 230. The results were as good as those obtained with a nitrided shaft having a Brinell of over 900. In these tests particular attention is paid to lubrication, and to oil cleanliness. In general, it may be said that with the harder bearing materials, such as copper, lead, lead bronze, and aluminium base metals, the harder the crankshaft journals and pins the better the results.

With a soft bearing material, such as tin and lead base Babbits, the degree of surface finish on the shafts is not so important as with the harder bearing materials. Apparently a ground finish will give as good results as a highly-polished finish when used in conjunction with the softer materials. Experimental work is now being carried out to check this. With the harder bearing materials, surface finish becomes of greater importance if excessive wear is to be avoided, especially during the running-in period.

Fatigue Strength

It is established that fatigue strength is profoundly affected by the presence of scratches or discontinuity on the surface. The influence of scoring upon fatigue resistance of the bearing material must therefore be considered. The higher the surface finish of a given material the greater the resistance to fatigue, but foreign matter in the oil may quickly destroy the finish and lower the fatigue strength. It should be pointed out, however, that for soft metals, such as tin and lead-base bearing metals, the effect of scratches is much less damaging than with the harder metals.

Consideration of the conflicting metallurgical demands upon bearing material indicates the result at which research must aim. This may be summarized as follows: (*a*) a bearing shell of great mechanical strength but of thin section; (*b*) a lining of bearing metal bonded to the shell and having a bond strength comparable to that of the lining material, for example, copper lead to steel; (*c*) the lining material should possess the frictional characteristics and embeddability of tin-base metals, the melting point of aluminium alloy bearing material (with the necessary precautions regarding local high surface temperature) and the load-carrying capacity of lead bronze.

It is apparent that bearing material development is moving along two parallel and complementary lines, metallurgical and mechanical.

SECTION THREE

Metallurgy of Machined Surfaces

During the past decade notable progress has been made in the field of metallurgy.

Both individual and co-operative research have resulted in a clearer understanding of the physical chemistry of steel making.

More attention has been given to melting, pouring and finishing temperatures, and scientific means are available for their control.

Steels with closer control of chemistry, grain size, normality, soundness and structure have been made available to meet exacting demands. In order to meet such demands the main considerations are design, materials and methods of manufacture, and only by the closest co-operation between design, engineering, metallurgy and machine shop can the most satisfactory results be obtained.

The engineer must design with full knowledge of materials and shop practice.

The metallurgist must select a material and heat treatment best suited for the particular design and method of manufacture.

The shop must manufacture to their required standards of accuracy and finish.

It is evident that the demand for lighter weight in certain branches of engineering design has grown during the past few years, and this demand has brought about the development of new kinds of steels and alloys.

In this Section an effort is made to display various fundamental phases of metallurgy applicable to machined surfaces without becoming too technical. Our first consideration therefore must be the fundamental structure of metals.

One of the best comparisons is that of a bar of metal and a piece of good-quality glass, which, if looked at in section with the naked eye, appear to be homogeneous, although they differ in the way they reflect the light.

But if a microscopic examination of each is made after an etching treatment a very considerable difference in structure will be seen.

The surface of the glass is still homogeneous in spite of any roughness due to the action of the chemical agent during etching, while the surface of the metal is no longer continuous, but is clearly seen as a series of irregularly shaped crystals or grains as indicated in FIG. 15.

FIG. 15.—Sketch of the grain formation of mild steel.

The fact that metals are of a crystalline grain construction has been known for a long time, but it is largely due to the untiring efforts of metallurgists in recent years that it is possible to know the fundamentals of metal structure, and the technique of determining the basic atomic structure of metals has undoubtedly led to some startling results.

In studying metals it is found that the crystalline structure falls into three main groups: (*a*) body centred cube (*b*) face centred cube and (*c*) hexagonal. These three groups are shown in FIG. 16.

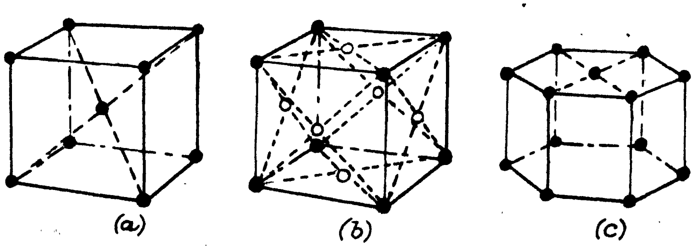


FIG. 16.—Crystalline structures.
(*a*) Body centred. (*b*) Face centred. (*c*) Hexagonal.

This crystal form determines certain physical factors of the structure as, for example, resistance to fatigue and heat.

When a piece of metal tends towards fatigue, a series of very fine cracks appear on the surface as a first sign, and the direction of these cracks is determined by the crystalline structure.

When metal is heated to melting point no rise in temperature takes place until the whole mass is molten in form, and in this condition the atoms are arranged in a haphazard fashion. But when metal is cooling it solidifies in crystalline form, which means that the atoms form a geometric pattern.

As these crystals commence at a large number of centres at the same time, the growth of each crystal continues until it collides with the neighbouring crystals.

In all crystals there are points or planes of weakness, which have a low resistance to shear, this being proved by the fact that failure of metal under stress occurs through the crystalline grains rather than through the area of the boundaries of the grains.

The four basic points in the crystalline structure are:

(1) The atoms are grouped in geometric units.
(2) These units are arranged symmetrically.
(3) In each crystal there is a point or plane of weakness.
(4) The direction of symmetry changes in different grains.

It is on these four facts that a basis is given to strength, ductility, hardness and other properties associated with each metal.

A study of the micro-photographs in FIG. 17, which deals with ·40 per cent. carbon steel, will clearly show the difference which takes place in the structure of the metal in the various conditions.

FIG. 18 deals with ·82 per cent. carbon steel in the same way, showing the structure of high speed steel in the varying conditions. This steel is commonly used for the manufacture of cutting tools.

From these photographs the difference in each grain structure by heat treatment plays an important part in the ultimate structure, which in turn affects the strength and other physical properties, as well as the machinability and final finish of the surface.

For example, gears have to be comparatively hard in structure, and therefore the choice of a steel depends largely on its properties after heat treament, and steels which are suitable for one of the hardening processes, such as (*a*) case hardening, (*b*) air hardening, (*c*) oil hardening and (*d*) nitriding, must be selected if satisfactory running conditions of the gears are to be obtained. Steels which flake under pressure of running together would be of little use for this type of work.

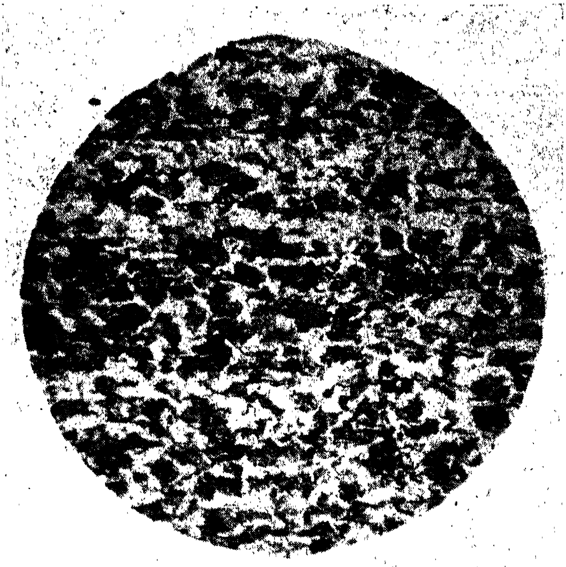


FIG. 17 (a).—Micro-photograph of ·40 per cent. carbon steel showing grain construction in rolled condition. (Mag. 250.)

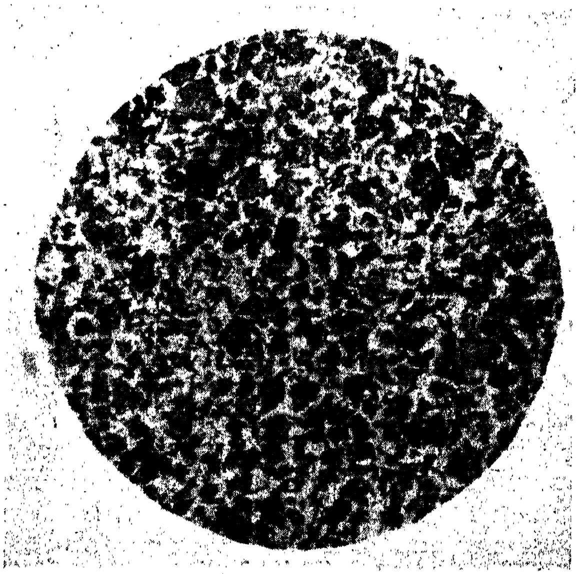


FIG. 17 (b).—·40 per cent. carbon steel after normalising. (Mag. 250.)
(By courtesy of The United Steel Companies Ltd. Research Dept.)

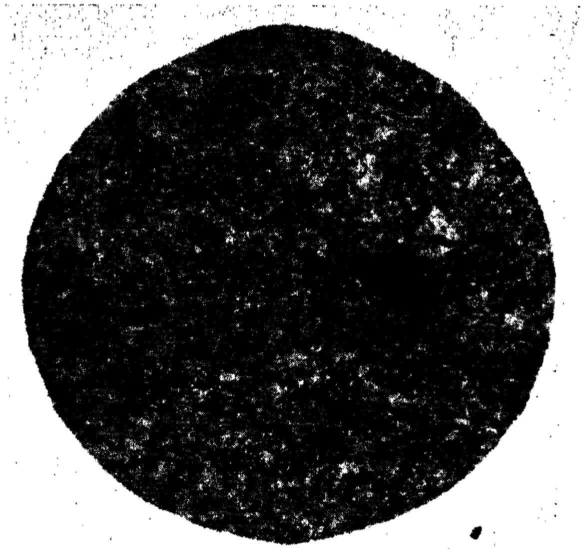


FIG. 18 (a).—Micro-photograph of ·82 per cent. carbon steel as rolled. (Mag. 250.)

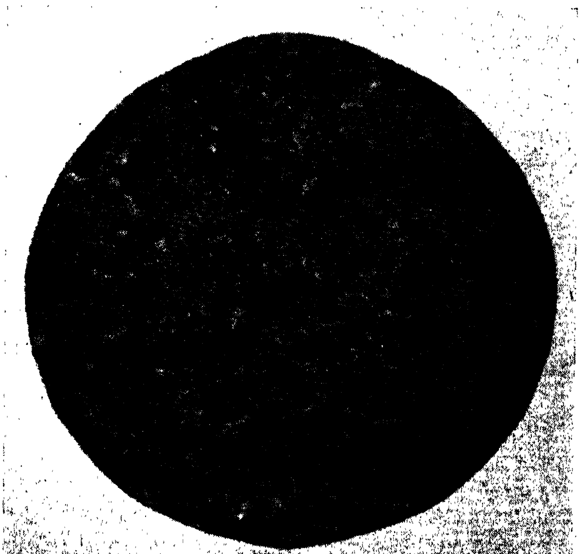


FIG. 18 (b).—·82 per cent. carbon steel after normalising. (Mag. 250.)

(By courtesy of The United Steel Companies Ltd. Research Dept).

FIG. 19 shows a very fine example of grain flow in the manufacture of an engine valve. It will be seen how the grain follows the required shape of the valve body thus ensuring the maximum strength in construction. In this process there are no ends of sections of metal to form weak points in the component.

Metals are relatively hard according to their nature, some of the softer metals being lead, tin and gold. But in engineering the hardness of most metals may be controlled by one of the above-mentioned heat treatments.

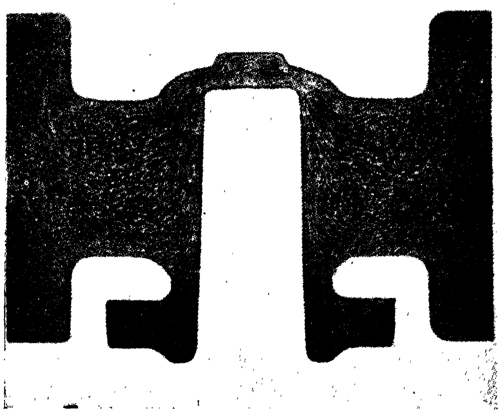


FIG. 19.—Grain flow in a valve body forging. (*By courtesy of the English Steel Corporation Ltd. Research Dept.*)

The main constituents of steel are cementite, ferrite, pearlite, austenite and martensite.

Cementite is in the form of iron crystals which are hard and brittle.

Ferrite is a collection of iron crystals which are soft and relatively weak.

Pearlite is a combination of cementite and ferrite.

Austenite is a solution of iron carbide obtained by heating the steel above the critical temperature.

Martensite is a solution of iron carbide, obtained by cooling the steel. Thus martensite is the main constituent of hardened steel.

To enable an insight to be obtained in what happens during heat treatment it should be remembered that, when steel is heated and cooled slowly, the pearlite and ferrite separate.

When cooling is carried out quickly, martensite conditions are obtained in the case of carbon steels and austenite conditions in the case of alloy steels.

When iron is heated no change takes place in the crystalline structure until a temperature of 910°C. is reached. Indeed no change occurs in the fundamental structure until 1,400°C. is reached, but if, for example, a carbon steel is heated to 35°C. above its critical and then quenched to harden, the austenite which it contained at the instant of quenching has no time to form pearlite and in consequence the constituent martensite is the result. It follows that since martensite is very much harder than either ferrite or pearlite, a good tool steel is produced.

We now come to the most interesting point in the structure of metals, namely, that carbon dissolves in face-centred crystals known as gamma iron, but is insoluble in body-centred crystals known as alpha iron, and since many ferrous metals used in engineering are alloys of iron and carbon, this is of the greatest importance to the engineer.

The operations of heat treatment allow grains a certain mobility, and through this mobility marked changes, such as have been seen in FIG. 19, occur in the structure.

Apart from the hardening methods mentioned above, there is another and more modern method of securing a satisfactory surface, the process of depositing chromium on the surface; very satisfactory results have been obtained on motor engine, aircraft and machine tool components, and also on cutting edges of such tools as drills and fluted reamers.

This method appears to have advantages in eliminating the structural troubles which so often occur in the high temperature hardening which is carried out for the purposes of securing a surface. The chromium is deposited on a suitable surface, and this is the secret of a satisfactory deposit. The surface must be smooth and clean before the deposit is made. The result of a rough surface is soon shown by the flaking of the chromium layer under the pressure of work.

It will be seen that if the crystalline structure of metal is subjected to a cutting action, removal of a certain portion of each crystal falling in the path of the cutter is inevitable, and to remove such portions of the crystal the tool can be a cutting edge type such as a lathe tool, or a milling cutter, and it may also be an abrasive type such as a grinding wheel.

The ease with which this penetration occurs depends to a certain extent upon the hardness of the stock and the tool. In general, for machining with carbon steel tools, metal cut should not exceed Brinell hardness figure 250, which is equivalent to a tensile strength of 120,000 lb. per sq. inch.

With high speed tools, and especially with cemented carbide and diamond tipped tools, steels of a much higher hardness figure may be readily machined.

The strength and toughness of the stock must be considered. After the cutting edge has penetrated the surface of the stock it must break off the resulting chip or turning: thus the material should be brittle and relatively weak for easy machining.

Since, however, metal can hardly be weak and brittle and at the same time possess all the characteristics required for its use in engineering, some constituent must be introduced to act as a chip breaker.

With this idea in mind, experiments have been carried out which have resulted in lead-bearing steels being produced having a high degree of machinability consistent with the required characteristics. During the production of steel satisfactory machining properties must not be obtained at the expense of either the surface finish or the physical characteristics, and with the lead-bearing steels these points appear to be satisfactory.

A development in lead-bearing steels is the addition of lead to low-carbon steel. This element is insoluble in carbon steel, but it may be incorporated as a suspension so finely disseminated throughout the metal that it is not distinguishable with a microscope. Such particles of lead appear to act as an internal lubricant and chips break off readily. Such a lead content is from ·10 to ·25 per cent.

Apart from this type of steel, the structure of stock to be cut seems to be a point for difference of opinion. One section considers that, of annealed medium and high carbon steels, those with completely spheroized cementite are the easiest to machine.

The other section maintains that as there are small isolated amounts of pearlite scattered through the spheroids of carbide the stock is easy to machine.

However, in general the rule that the higher the tensile strength the lower the machinability may be safely followed.

Another factor which enters into the machining process is the size of the grains or crystals. It is true that higher cutting speeds can be safely used for coarse-grained metals, especially steels, than for fine-grained metals; but when the finish of the surface in the machining operation is a very important factor, a fine-grained steel will be found the most satisfactory.

A good example of a fine-grained steel is found in the ball bearing industry, and in this case the bar stock for races is specified as annealed to a spheroidized structure. A very general composition of such steel is: Carbon ·1 per cent., Manganese ·35 per cent., Phosphorus ·03 per cent., Silicon ·23 per cent. and Chromium 1·3 per cent.

How, then, can the finished surface of steels affect the designer?

This may be considered a very broad question, and we may narrow it down to designers of machine tools and motor vehicle engines.

Certain conclusions may be drawn from the machining operations described in SECTIONS 4 and 5, where it will be noted that the improvement in surface quality increases in each succeeding process, this being borne out in FIG. 91.

Given a surface relatively free from fragmentation we can be assured of a reduction of friction between the two parts, such a reduction enabling a designer to put into practice many designs which were previously just not possible.

Because of the resulting reduction in stresses by the reduction of friction, lighter designs may be introduced, lighter bearings with greater strength, lighter castings, higher running speeds; all may be obtained by the careful considerations of the surface.

Thus it may be seen that the construction of the metal has a direct bearing on the ultimate surface obtained, and the physical properties of the metal must always be considered in the design of practical parts and components.

Much attention has been paid to all these points as well as those included in the general term "machinability". The range of technical publications is on the increase, but much still remains to be done both by the metallurgists and by the engineers.

Certain useful properties of metals are listed below with a short description of each property:

Electrical properties.—The actual value of the metal in conducting electricity.

Compressive stress.—Two parts pushed towards each other in a perpendicular direction to the plane of reference.

Tensile stress.—Two parts being displaced in a perpendicular direction from the plane of reference.

Stress.—A load applied to a body gives rise to a quantity of internal forces, such forces or stresses producing relative displacements in parts of the body.

Thermal conductivity.—Measured in terms of heat conducted through a section of given area and thickness for a given temperature gradient in a given time.

Co-efficient of linear expansion.—The change in the linear dimensions per degree of temperature change.

Deformation—Occurs when a stress in a body is accompanied by a change of the external form.

Cold work—The permanent deformation of metal at any temperature below the annealing temperature.

In a close study of a smooth surface of metal two conditions may be recognized: primarily, metallurgical conditions include the original crystalline formation with the amorphous cement which has been formed through the heating and cooling of the materials comprising the metal; secondary conditions include the making up pertaining to surface characteristics which have been changed by machining operations.

The operation of the outer layer of steel due to the stress intensity and distribution associated with the various machining operations, results in a layer consisting of deformed metal, called throughout this book "fragmented metal" or "fragmentation". This fragmentation varies according to the particular operation. If heavy cuts are taken from the workpiece the deformed layer which remains is thick and irregular, while if light cuts are taken then only a thin layer is left on the surface of the workpiece.

A certain amount of confusion appears to have occurred in the uses of the terms "fragmented metal" and "smear metal".

Fragmented Metal is the crystalline metal in which a certain amount of crystals remains as a unit, but may be loosened, disrupted or crushed, and are thus combined with the amorphous material.

Smear Metal is, in effect, fragmented metal which has gone one stage further by flowing under the action of speed and pressure which creates heat, with the result that the layer is no longer crystalline in structure, but takes on a vitreous form.

Pen records taken on a surface meter are given in SECTION 6, and when studying these it is well to remember that they are actually the profile of a machined surface and that they give the profile of the fragmented metal.

Consideration must be given to the degrees of micro-profile and macro-profile of machined metals, which allow a considerable number of combinations of surface conditions resulting in the various surface qualities.

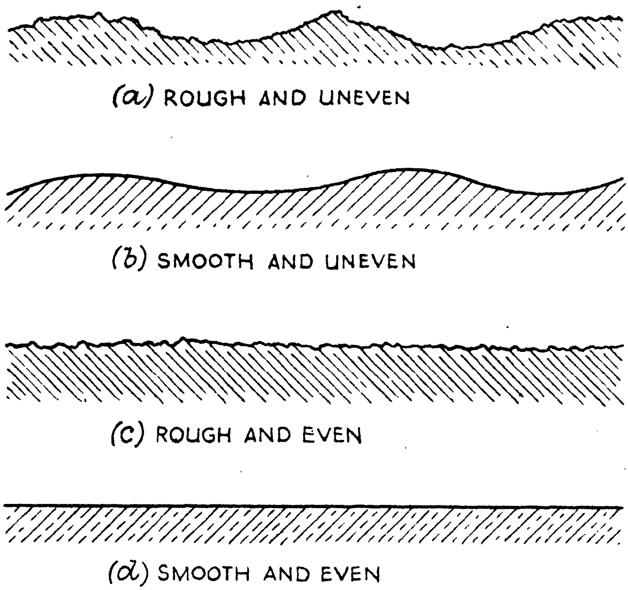


FIG. 20.—The four main groups of surface profile. Macro is indicated in (*a*) and (*b*), whilst micro is shown in (*c*) and (*d*).

Broadly, surfaces may be rough and uneven; smooth and uneven; rough and even; smooth and even; and these four main combinations are shown in FIG. 20.

The measuring of surfaces is based on the mathematical calculations of these conditions, and the considerations in SECTION 7 will be closely allied to this Section.

Consideration of the shearing action of a single point cutting upon the crystalline structure of a piece of metal is made possible by the examination of a photomicrograph such as FIG. 21, which clearly indicates the torn and fragmented metal. It follows that if high temperatures are involved in the splitting off of the metal turnings the inner layers must in some way be affected.

The outer layers consist of peaks and valleys due to the structure being mutilated, and the inner layers, which serve as a bond for the outer layers, have to take the stress imposed by both pressure and heat.

Recent research into the effect of machining on surfaces has been carried out by a technique known as electric diffraction. Briefly, a defined beam of electrons fall on the test surface and is reflected on to a photographic plate, the diffracted electrons producing a series of bright and dark rings around a centre spot.

One use of this technique is to decide the type of metal structure, that of austenitic structure having crystals made up of cubic elements with one atom at each corner and one in the

FIG. 21.—Sketch of a rough turned surface.

centre of the cube, whilst that of ferrite structure has crystals of cubic elements with one atom in each corner and one atom in each cube face.

By applying the technique to a ground surface of fragmented austenite crystals the depth of overheating in the metal was measured to ·0003 in.

The use of high speed photography shows that when a crystalline structure of a piece of metal is mechanically treated or machined, the effect of pressure and speed produce heat; and this may be sufficient to cause a reduction in grain size on the surface. This in turn results in the structure of the surface metal being different from that of the bulk of the metal, while the existence of thermal stresses has been proved.

To summarize the resulting action of the speed and pressure of metal machining from a metallurgical standpoint: the heat generated forms a layer of fragmented metal, which has been changed in structure due to the heat treatment received during the shearing action of chip removal, with a consequent mutilation of each surface crystal. Stresses have been set up in the crystals of the surface which may penetrate to some depth, such penetration varying according to the metal used and the method of machining.

For finishing, it would appear that a method is required which will remove this stressed and deformed surface metal, thereby producing a surface which is smooth and crystalline in form.

Such a method may be lapping, superfinishing or fine surface finishing.

Inclusions

One aspect in the relationship of metallurgy to surface finish has been indicated during recent research, i.e. the presence of inclusions in the metals used for certain components.

These inclusions are generally in the form of hard grains of foreign material which, when machined, frequently become dislodged, leaving a distinct cavity in the surface of the component part.

The presence of inclusions in either ferrous or non-ferrous metals is bound to affect the final results. Apart from the fact that cemented-carbide tools and diamond tools are invariably damaged, the problem must be studied closely in the interests of economy and reduction of scrap.

It is generally recognized that inclusions arise from refractory material of crucibles and furnaces or from oxidization of the alloys.

Much has been done to avoid these formations by the use of suitable flux treatments and manipulation of the alloys in the foundry.

With the wider use of diamond cutting tools in production work, the desirability of ensuring that these hard grains do not develop calls for the closest co-operation of all concerned in the production of the material either for castings or forgings intended to be machined with the aid of diamond tools.

SECTION FOUR

Machining of Surfaces

In order to have a clear understanding of the production of working surfaces of component parts, methods and processes must be considered by which such surfaces can be obtained.

The formation of a component may be completed by a number of operations on a number of machines, while the material used must have the physical properties demanded by the work for which it is intended.

The application of machines used to produce size, shape and surface quality are varied, but the method of actually removing the metal and finishing a part may be considered in two classes.

The first class is the method considered throughout this book, known as the Chip method.

Operations of this method include Turning, Milling, Boring, Broaching, Drilling, Grinding, Honing, Lapping, Planing, Shaping, Reaming, Tapping, Threading, Fine Surfacing and Superfinishing.

The Chipless method includes Polishing, Pressing, Rolling, Casting, Burnishing, Forging.

The Chip method may be divided into two broad headings.

(1) Producing a chip by a cutting tool which is harder than the material being cut.

(2) Producing a chip by an abrasive action, the abrasion being harder than the material being cut.

In the first class are Turning, Milling, Boring, Broaching, Drilling, Planing, Shaping, Reaming, Sawing, Threading and Tapping.

In the second are Grinding, Honing, Lapping, Fine Surfacing, Superfinishing.

Turning

This method is probably one of the most widely used for stock removal, and is carried out on a machine which revolves a piece of stock, while a suitable cutting tool is pressing against it, the tool removing a shaving of metal from the piece of stock.

To indicate the great advance in progress, a brief history is given, and it is interesting to note that with each advance a general forward step has been taken by the engineering world.

Probably the French were among the first to use something in the nature of a screw-cutting lathe as far back as 1570, such a machine being constructed of timber. In 1797 Maudslay built quite a good lathe, certain parts of which were metal, and he further improved on this about 1800 by producing a screw-cutting lathe.

The refinement of what we know as back gearing was credited to Roberts in 1818, and 1900 saw the introduction of a step-cone drive.

The modern lathes are production machines in the main and demand extreme accuracy of construction. This is accomplished by the scientific application of weight and rigidity, coupled with precision bearing, a wide range of headstock speeds, automatic control, and in most cases individual electric motor drive.

An ample coolant supply system, often automatic in operation, provides one means of obtaining the high quality of work which a production lathe is called on to produce.

A workshop lathe is in general for workshop use, and it is on this assumption that all lathes are built, whether they are for special purpose work or not.

The headstock is capable of being moved along the bed and fixed rigidly at any desired position. The cutting tools are held in place in a toolpost which is adjustable so as to ensure that the tool is in correct relation to the workpiece. This latter point is important.

Inaccuracies between tool and workpiece often can cause chatter marks on the surface of the work, and factors which control the finish obtained are:

(1) The condition and rigidity of the machine.
(2) The class of material being cut.
(3) The type and condition of the cutting tool.
(4) The type and application of a coolant.
(5) The speed of the workpiece and the feed of the tool.

Generally the part requires to revolve at speeds ranging from 50 to 500 ft. per min., this speed frequently controlling the depth of cut and rate of the feed; but it becomes increasingly difficult for a tool to cut cleanly it if has to remove less than ·005 in.

In order to overcome the formation of fragmented metal on the surface, fine turning, using a diamond tipped-tool, is often employed, and such tools are being used in ever-increasing numbers because of their particularly useful characteristics of hardness and toughness.

These tools operate at high speeds with fine feeds, and the stock removal varies between ·003 and ·008 in diameter.

With the high speed and considerable pressure of the tool on the workpiece heat is generated in both the surface layers of metal and a number of the inner layers. The surface temperatures range from 600°F. to 1,000°F. and it follows that such temperatures will produce considerable surface ductility which may extend in depth from ·010 in. to ·125 in.

It follows that the surface will be susceptible to surface scratches during any process which follows, while the formation of the layer of fragmented metal is the natural outcome of the tool shearing away the chips, especially when dealing with ferrous metals.

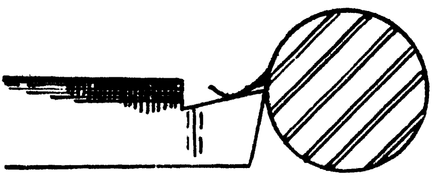


FIG. 22.—Turning (cutting process).

In order to obtain high quality surface finish on certain types of materials by turning operations the use of diamond tools has done much to assist the productions on a quantity basis while retaining the quality, and research has been carried out, with the aid of suitable surface recording equipment, to determine the effect of varying the operating conditions.

In respect of the cutting edge, experience has shown that in order to maintain high quality surface finish the edge must be dimensionally accurate and optically perfect at 100 magnifications.

Any deviation from either of these requirements will be reproduced on the surface of the workpiece, therefore the effects of diamond tool design and setting are the subject of part of SECTION 9 (Research).

Milling

This is the second of the cutting operations in wide use, differing in principle from the lathe in as much as the lathe tool is in constant contact with the workpiece during the chip removal, whereas the milling cutters take a series of intermittent cuts due to their construction, which is cylindrical and the serrations or teeth on the edge.

Milling machines are built under four groups: (*a*) Universal machines, (*b*) Vertical milling machines, (*c*) Plain milling machines, and (*d*) Production or special purpose machines.

As with turning, the speed of cutting is an important factor in the resulting surface produced.

It is on the careful choice of proven cutting speeds in relation to the feed of the tool that the success of cutting may be assured, with the minimum of structural disturbance of the metal being cut.

The type of cutting edge for milling tools has progressed over the years, and SECTION 9, devoted to Cutting Tools, considers the modern practice of negative rake milling, in as far as the latter has been used for practical work.

In these notes normal milling practice is considered, and one important operating feature is the use of cutting speeds. These are high for non-ferrous metals and low for ferrous metals. As a guide to cutting speeds, roughing cuts in feet per minute are: for Cast Iron 40, and for Mild Steel 60. For finishing cuts these are increased to 50 for Cast Iron and 80 for Mild Steel.

Among the other practical operating features which have to be considered are the sharpening of cutters which requires care peculiar to each type of cutter, the machining slides, which demand adjustment and adequate lubrication, the alignment of both the workpiece and machine, and the cutter setting which ensures that the depth of cut is accurate.

The development of the milling cutter has progressed, one of the most useful improvements being the number of teeth employed. At one time milling cutters were considered as a form of saw, but it has been found that only a few of these teeth actually cut while those which drag have a tendency to work harden the component surface, which in turn quickly destroys the cutting edges of the cutting teeth and also generates heat which is distributed through the cutter, coolant, workpiece and any resulting chips. The introduction of cemented carbide tips to milling cutters has made for a change in practice, because this type of tip, with positive axial and radial rakes, has failed in operations due to insufficient support being given to the cutting edge. Also the intermittent action of each cut tears the tip from the seating.

Cutters have had to be re-designed to overcome these failures, and the method of doing so is described in SECTION 9 (Research). Negative rake cutters are at present still in the development stage.

Briefly the exact operation of any type of milling machine is that a milling cutter of required shape revolves on the spindle of the machine. The work is brought steadily into contact with the revolving cutter by the work-table on which the workpiece is clamped.

In the case of a universal machine the work-table can be swivelled to a fairly wide angle in the horizontal plane to enable helical grooves or slots to be milled.

The range of cutting speeds—*i.e.* the speed at which the cutter revolves in feet per minute—is normally provided by a gearbox, and the feed—*i.e.* the rate at which the workpiece is fed into the cutter—may be controlled automatically or by hand.

There are numerous ways in which the work may be held to the work-table. It may be fastened directly to the table, which is provided with T Slots throughout its length, or it may be held in a fixture fixed to an angle-plate, held in a vice, or between centres, especially when indexing operations have to be performed. Whichever method is used, rigidity of the work is essential, and any tendency for the work to spring under the action of the cutter must be eliminated with suitable jacks or packing blocks.

Indexing is carried out by the use of a dividing head which rotates the workpiece on its axis to the exact amount required, such operations include fluting, spline milling and gear cutting.

The intermittent cuts start at infinity and gradually pick up the shearing or cutting action in order to produce the chip. The series of operations of each tooth is a sliding action followed by a crushing action as the tooth penetrates the workpiece. This is followed by the shearing action.

This peculiar series of actions produces a hardening of the surface, known as " work hardening ", which has to be taken into consideration when designing milling cutters for use with certain materials.

Boring

This is a cutting operation intended for internal work, used for giving required dimensions to bores.

The operation is in most ways identical with turning, except that differently shaped cutting tools are required, in order to ensure that the tool cutting edge is in constant pressure with the bore.

Fine Boring

The following remarks on the fine boring method indicate that the machining stresses imposed on the metal structure of the workpiece must be kept to the minimum if distortion is to be controlled.

The principal factor is the use of a high-speed spindle, coupled with a very fine feed, and a light cut. This allows very light clamping of the workpiece, which naturally lessens the possibility of distortion in the bore when the clamps are removed, thus assisting in accurate machining. The resulting finish of microscopic thread-like appearance around the surface of the bore is obtained by the correct shape of the diamond cutting tip, a steady fine feed, and the tool spindle in first class condition.

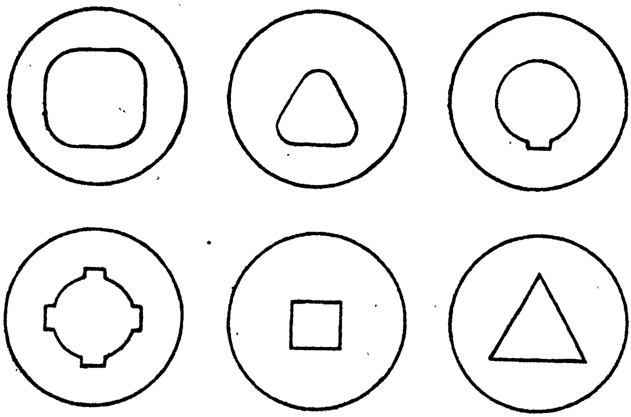


FIG. 23.—Examples of regular and irregular shapes produced by internal broaching.

Broaching

Broaching is a method of altering the size or shape of internal work in metal by the operation of pushing or pulling a tapered cutting tool or broach through the work.

The teeth are progressively increased in size toward one end of the broach.

Many shapes of internal work or holes may be produced by internal broaching, as shown in FIG. 23, which indicates squares, splines, and so on. Keyways are commonly formed by broaching.

FIG. 24 indicates the terms for the parts of a broach, and also indicates the general clearance required to ensure clean cutting. Where a superior finish and close internal dimensional accuracy is vital, a burnishing broach is employed. This is similar to a cutting broach, except that the cutting edges are replaced by burnished rings.

Surface broaching.—Certain advantages may be secured by the use of surface broaching on various components, and although this method is employed on quite a number of components, its full advantages have not yet been fully realized,

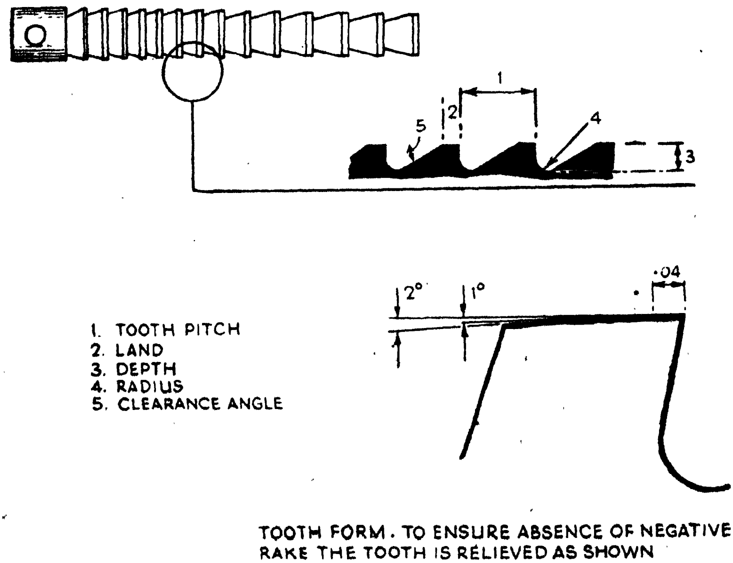


FIG. 24.—Details of a broach.

although attention is being given to the wider application of the process in view of the high production rates which can be obtained when compared to performing the same operation with a milling machine.

Accuracy of machining is in some measure controlled by the rigidity of the machine and, in view of the type of operating motion used in a broaching machine, the maximum rigidity can easily be obtained.

The actual stock removed is progressive, and the amount can be adjusted so that no cut is heavy enough to cause distortion.

FIG. 25 indicates the types of irregular profiles which may be easily surface broached, and shows an engine connecting rod wholly machined by this method, except for small holes which are drilled. These parts are manufactured at a considerably lower cost than by the more usual methods of milling, especially when considering quantity production of, say, 2,700 per week. Such a quantity would require special layout and machines whichever method were used, and by comparing the cost of each type of machining and machine tool required, together with its tool and layout cost over the required operations, considerable savings can be obtained by broaching. Factors which have to be decided when considering the broaching operation include: (*a*) the machinability of the metal, (*b*) the amount of stock to be removed, (*c*) the suitability of the component to ensure accurate and speedy loading in the machine fixtures.

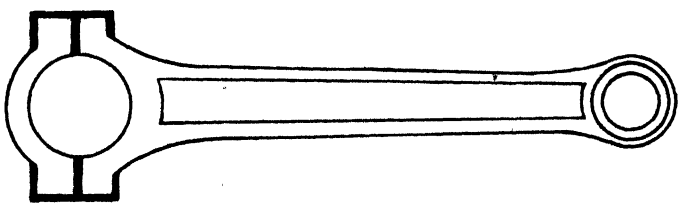


FIG. 25.—Surface broaching of a connecting road (thick lines).

Such fixtures must be considered upon the individual merits of the job, but the following general principles are considered in their design. Rigidity is of prime importance to both the life of the broach and the quality of the work. When using the clamps, at least one should be so located that it will resist the pull of the broach. Even if clamps are not employed, the design of the fixture should be such that it will ensure resistance against the pull of the broach during the working stroke.

The use of hydraulically operated fixtures assists in the reduction of loading and unloading times, as well as the broaching of more than one component at a time.

Practical comparisons of the production rates of components are as follows: Motor vehicle gearbox. Machine face and two sides to remove $\frac{5}{32}$ in. to $\frac{1}{4}$ in. of metal. By broaching rate, 22 per hour; by other methods, 5 per hour. Shaft. Machine two flats on a steel shaft removing $\frac{5}{16}$ in. by $\frac{1}{4}$ in.

of metal from each flat. By broaching, 460 per hour; by other methods, 97 per hour.

Other production rates which compare favourably include: round holes in laminated roters for electric motors, 250 per hour; steering column having 36 splines, 98 per hour.

Broaches

Broaches are in general a special-purpose cutting tool, each tool being considered and designed upon the merits of the work it has to do. In the manufacture of these cutting tools four factors must be considered: (*a*) Design, (*b*) Material, (*c*) Heat treatment, (*d*) Grinding. High-speed steel is used, and a usual analysis is Carbon ·70 per cent, Tungsten 18 per cent., Chromium 3·5 per cent., Vanadium 1 per cent.

If this steel is subjected to careful heat treatment it will have a Brinell hardness number of about 220, and should therefore be easily machined.

Broaches are used after being hardened and tempered, and it must be stressed that a broach is an expensive cutting tool, so that the heat treatment must be carefully controlled.

Cast iron is used as a main body when cemented carbide tips are used, especially in finishing work.

The tooth form is related to planing, slotting and shearing tools, and the chip produced is tightly curled due to the shearing angle combined with a curved lip.

A typical tooth form to give a tightly curled chip requires the pitch of the teeth to be sufficient to allow adequate chip clearance, but at the same time it should be fine enough to ensure a minimum of three teeth cutting at the same time. Each tooth rises slightly from the preceding one, and the main factor which governs this rise is the amount of stock removal required.

In common with other cutting tools, grinding of the cutting edges of a broach is of prime importance, because, being a multiple cutting tool, every edge must be ground to the correct angle. The major factor, however, lies in the grinding of each tooth in true relationship to the one immediately ahead and behind it. As the grinding of the teeth has such a marked effect upon the cutting powers of the tool, it will be seen that the requirements are much more severe than is the case with any other cutting tool edge. The pitch between the teeth, as well as the taper of the tool, has to be accurately preserved, and in consequence special broach grinding machines have been developed to assist the accurate maintenance of size and shape. It will be seen that the aim in sharpening is to restore the initial keenness of the edge and at the same time maintain the true dimensions as closely as possible.

The choice and application of a cutting fluid is dependent upon the type of material being cut, and is dealt with at some length in SECTION 9 under the head of Cutting Fluids.

Drilling

Drilling is an operation for the production of a dimensional hole in material, and the cutting tools or drill used, may be of several types. The most commonly used type for metal work is the twist drill, shown in FIG. 26.

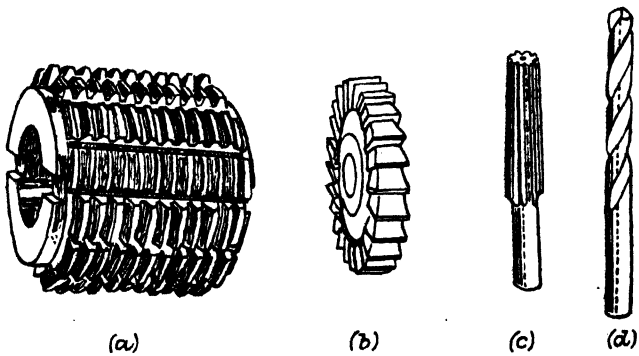


FIG. 26.—Standard cutters. (*a*) Gear hob. (*b*) Milling cutter. (*c*) Taper reamer. (*d*) Twist drill.

Considerable care must be taken in sharpening twist drills to ensure the maintenance of the cutting angles, and this is dealt with at some length from a practical standpoint later in this SECTION.

It will be seen in FIG. 27 that if the cutting angles are not identical the hole will tend to become larger than is required, and also the drill will wander off centre.

Again the cutting speeds and feeds of the drilling machine must be carefully controlled to obtain the maximum production of accurate parts.

Drills.—In view of the common application of a drill for obtaining a hole in metal, it is often forgotten that the factors of heat and power are involved in its correct working.

As with other cutting tools, friction is set up between the drill and the workpiece, and is dispersed in the form of heat. The dispersal includes the radiation of the heat, and it has been found by experiment that the ability of drill surfaces to radiate the heat depends largely upon the actual surface conditions.

To obtain the maximum efficiency from a correctly made twist drill, it is necessary that it shall be kept keen, and requires correct grinding at the cutting edges and point.

FIG. 27 shows the correct cutting angle to produce a clean and true dimensional hole.

If the cutting edges are unequal in length it follows that the point will not be central, and the resulting hole will be larger than is required, being anything up to ·010 in. larger.

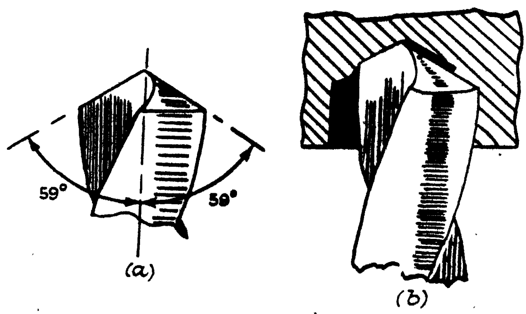


FIG. 27.—Drill cutting angles.
(*a*) Equal angles—correct. (*b*) Unequal angles—incorrect.

Speeds for drilling conform to other cutting tools in that no set rules can be laid down. The composition of the workpiece and its hardness, the depth of the required hole, type of coolant, the machine and its conditions, the maintenance of the cutting edge, are some of the variables which must be considered.

Certain difficulties may arise when drilling such materials as austenitic stainless steel, but there are several general factors which must be accounted for. Twist drills of 18 per cent. tungsten high speed steel may be used, and these must be kept sharp so that excessive heat is not generated by any rubbing action, otherwise work-hardening will take place in the steel, which may make it almost impossible to drill.

Cutting Tool Surfaces

Experiments carried out from 1943 onwards bear out the theory that the welding together of minute spots of the rubbing surfaces of the tool and workpiece occurs frequently. Assuming that this minute welding does take place, it follows that heat is generated and that the surfaces are clean and free from lubricant, such a state being brought about by a failure in the lubricating film. Taking this a stage further, there is a softening of the surface of both tool and workpiece, and the effect of such surface ductility is to increase the area in which the welding takes place.

FIG. 28.—Turning being removed by a lathe tool. Note the type of surface of the workpiece as the metal is cut away.

Experiments on twist drills and the destruction of their cutting edges show that the collapse of these is frequently due to the grinding process used to produce the edge, which generates heat at points where it is not desirable.

Summary.

It will be seen that in order to cut satisfactorily the edge of the modern lathe tool must have a shape which will produce a turning while it is continually bearing against the workpiece, and it must also guide this turning away from the main part so that no obstruction takes place.

It has been made clear that the use of metal surfaces in pairs results in metallic pressure, and in each of the machining methods stresses are set up by the pressure of the cutting tool upon the workpiece.

This pressure (all other things being equal) produces a certain amount of deformation of the crystalline structure of the workpiece resulting in the production of a turning or chip, and this production is in the nature of a shearing away of the chip rather than a true cutting action. Mechanical factors which influence the surface are the hardness, size, shape, angle and rake, the speed and feed of the tool, the depth of the cut, and the nature of the coolant or lubricant.

The illustration (FIG. 28) shows the actual turning coming away from the workpiece, and the type of surface left by the taking of heavy cuts is shown in the nature of a thread on the surface of the stock. Most of the results in ascertaining just how the chip comes away have been obtained by the use of high-speed cameras, which place on record the actual cutting action, as well as recording the types of cut obtained by varying the cutting angles of the tool on different types of metals, and these results are discussed fully in SECTION 9.

One important fact arises from a study of these methods of surfaces finishing: no matter how fine a surface is ultimately produced, metal is removed each time the tool touches the workpiece, and a change in dimension is produced.

SECTION FIVE

Grinding

PROBABLY the most widely used method of dimensional correction and surface finishing at the same time is the grinding operation, using an abrasive material which is in line contact with the work.

Many types of grinding operations are performed, including flat, cylindrical, internal and cup grinding. But whatever types are used the problems which arise are the same.

Demands for large quantities of accurately dimensioned metal parts have steadily increased the importance of grinding, and operations such as thread grinding, gear grinding and certain types of form grinding, employ wheels travelling at high velocity which remove the metal at surprising speed and accuracy.

Commercial grinding operations are performed at speeds ranging from 50 to 200 feet per minute, whilst the abrasive wheel revolves at a surfaces peed ranging between 3,000 to 8,000 feet per minute, and the pressure between them may be up to 1,000 lb.

The grinding action, in effect, removes a quantity of very minute chips similar in many respects to those formed during the turning operations, and this operation of a multitude of single point cutters brings about a fragmented surface, as is seen when the surface is measured by a surface meter such as is considered in SECTION 6.

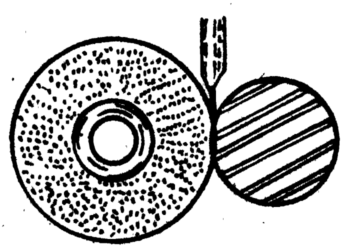


FIG. 29.—Grinding (abrasive process).

Heat generated in the workpiece, and the change in temperature, will vary from 6,000°F. to 8,000°F., which, as we have seen, causes surface ductility; and the depth ranges from ·0005in. to ·003in. The pressure is spread over a larger area than in the case of turning and the heat conductivity is better controlled, thus making the cuts more shallow, although the type and quality of the abrasive material and the relative hardness of the part have important functions in the final finishing results.

For external grinding the revolutions per minute of the work may equal $\frac{160}{D}$ where D is the workpiece diameter in inches, and it should be remembered that in the calculation of some of the grinding formulæ the width of the grinding wheel plays an important part.

Precision grinding machines are designed to ensure extreme accuracy in the relationship between the wheel and the work. The abrasive material takes the form of wheels composed of particles of abrasive grit suitably bonded together. A series of numbers and letters will be found on the label affixed to the wheel, and the standard markings are in the following order:

Abrasive letter.	Grinding Size No.	Hardness or Grade	Structure or Density	Bond or Process.	Maker's Record.

In general, the higher the grain number the finer the wheel, and in respect of the abrasive letter hardness or grade, the letter A indicates the softest grains while the letter Z indicates the hardest.

The abrasives used in the manufacture of grinding wheels fall into two categories: (1) Natural abrasives, which include emery, solid quartz and corundum, (2) Synthetic abrasives, which consist of alumin-oxide and carbide of silicon.

Emery, which is obtained from Turkey, is a tough abrasive but contains such a quantity of impurities in its natural state that its properties cannot be easily controlled.

Corundum is the second hardest known material, being only exceeded by the diamond, and is found in commercial quantities in India, Canada and the United States of America. Its basis for a cutting action is crystalline alumina.

Alumin-oxide, or crystalline alumina, is made by the fusion of bauxite in an electric furnace.

By processing the natural bauxite with ground coke and iron filings at a temperature of 1,650°C. in two-ton lots, a solid mass of crystalline material of about 94 per cent. alumina is formed, and after this has cooled the residue is crushed, which results in the base material for the abrasive.

Having graded the abrasive it becomes necessary to bond it into the shapes required. About half the grinding wheels produced are vitrified bonded. Two other types of bonding are silicate and elastic.

Vitrified Bonding

Vitrified bonding consists of mixing abrasive particles with a suitable clay, and adding the correct amount of water while the mixing is taking place. This mixture is then poured into moulds and passed through a series of carefully controlled drying operations. By reason of this method of manufacture, vitrified bonded wheels are not affected by either the working temperatures, climatic conditions, water, oil or acid.

This type of wheel is usually dark brown in colour.

FIG. 30.—Surface effect of out of round and out of balance in wheel.

Silicate Bonding

Silicate bonding of wheels is processed in a similar manner to vitrified bonded wheels, but the bonding medium consists of silicate of soda. The colour is usually light grey.

Elastic Bonding

This type of wheel has a certain amount of elasticity, and the bonding medium has a base of either rubber, resin or shellac.

With regard to the speed of grinding wheels it is essential that the manufacturers' rating should not be exceeded, as these ratings are based on the safe maximum speeds.

The increased use of tungsten carbide tools for lathe work brought about the introduction of diamond dust cutting wheels. This type of wheel has the distinct advantage of cutting freely at lower temperatures, while during the actual grinding practically no particles of the abrasive are freed, because a diamond wheel has very little wear during the grinding operation.

Since the action of high speed grinding induces heat in the workpiece, the introduction of a coolant of either water, or

FIG. 31.—(a) Commercial grinding without filtered coolant. (*By courtesy of Carborundum Co. Ltd.*)

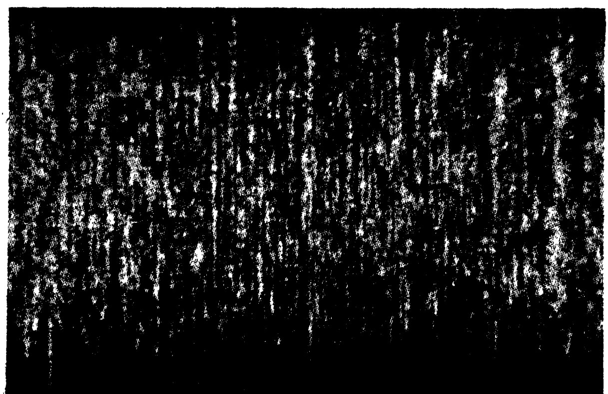


FIG. 31.—(b) Commercial grinding with filtered coolant. (*By courtesy of Carborundum Co. Ltd.*)

water soluble oil, is found to be necessary, and the function of such a coolant may be considered to be threefold:

(1) To reduce the temperature of both wheel and workpiece.

(2) To maintain a uniform temperature and prevent local rises in temperature.

(3) To carry away particles of metal and abrasive.

The flow of the coolant to the work must be constant and uniform, as fluctuations result in variations in the heat of the workpiece surface which may in turn result in a change of dimensions.

The use of correct coolants for metal machining operations is becoming of greater importance with the increased speeds and high production rates.

Plain water when used for cooling has the disadvantage of turning the workpiece rusty in a very short time, so that a suitable soluble oil is generally introduced.

Precision Grinding

Where grinding is the final operation on component parts for both dimensional and surface finish, precision grinding

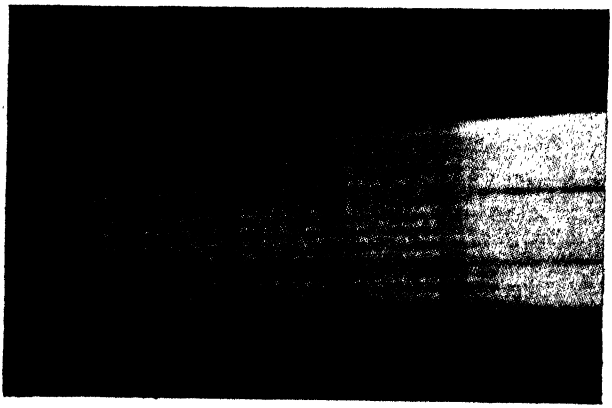


FIG. 32.—Surface " chatter " marks caused by glazing or loading of wheel.

becomes a matter of importance, especially where the requirements are dimensional accuracy, rate of output and final finish.

While the depth of cut depends upon the type of material which is being ground, it is reasonable to allow between ·004in. and ·006in. for stock removal.

Modern precision grinding machines demand weight and rigidity coupled with extreme accuracy during manufacture, because the surface finish produced is in effect a reproduction of the grinding wheel, and in the case of cylindrical work the grinding wheel spindle must be true and the grinding wheel a perfect cylinder, or good results cannot be obtained.

Dealing first with external cylindrical grinding, the factors which govern the quality and output of work include the type of grinding wheel, its speed, grade, diameter, and width, the table speed, the work speed and the coolant or lubricant.

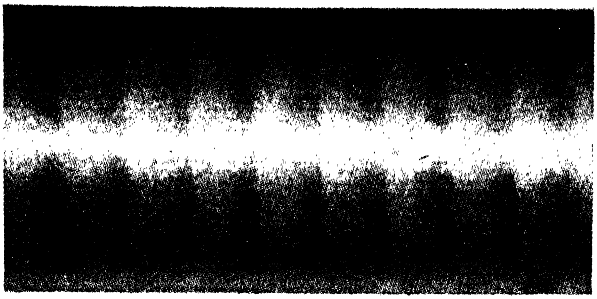


FIG. 33.—Surface traverse lines caused by faulty wheel dressing. (*By courtesy of Carborundum Co. Ltd.*)

The grinding wheel speed is directly governed by the rigidity of its spindle head, for example on a machine of light construction a speed of 6,000 ft.may be required to obtain results similar to those obtained on a heavier constructed machine at 5,000ft. per min.

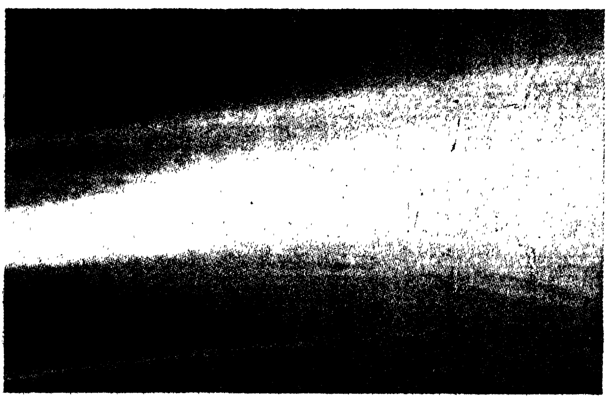


FIG. 34.—Traverse lines caused by wheel dressed on a taper. (*By courtesy of Carborundum Co. Ltd.*)

The grade of wheel grit for precision work must conform to the conditions of each batch of work, and guidance in this matter is always obtainable from the manufacturers of grinding wheels. In general, it is better to use a wheel which is too soft rather than too hard. A wheel which is too hard will be found to glaze rapidly.

With regard to the coolant, especially if water is used, a plentiful supply without force is required.

The finish of crankshafts is one class of work to which the precision grinding is particularly applicable, and cam grinding is also another very successful operation.

Centreless Grinding

This method of precision grinding eliminates the use of centres for holding the workpiece.

Two wheels are mounted face to face, one a grinding wheel and the other a regulating wheel. Both revolve in the same direction, the grinding wheel at speeds between 5,400 ft. per min. and 6,000 ft. per min., and the regulating wheel at between 30 and 500 ft. per min.

The four methods used on centreless grinding machines are: (1) Through feed, (2) Infeed, (3) End feed, (4) Concentric.

The through feed method is used for such parts as pistons, gudgeon-pins, rollers and straight bars.

Infeed is used for spherical, tapered, multi-diameter and irregular profiles. The regulating wheel is inclined at an angle in relation to the grinding wheel.

The end feed method is used on taper work, and the grinding and regulating wheels are set and trued to give the required taper.

Concentric grinding enables outer cylindrical surfaces to be ground concentric with previously determined bores.

Factors which govern precision internal grinding are similar to those for external work, and it is of extreme importance that the grinding spindle for this class of work be accurate and balanced. In general these spindles are run on pre-loaded ball bearings.

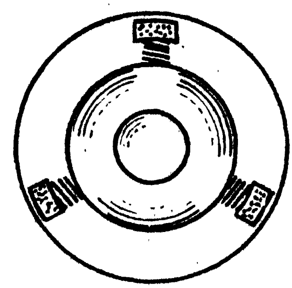


FIG. 35.—Honing (abrasive process).

The following information on common errors in precision grinding is supplied by the Carborundum Company Limited and is reproduced from their booklet.

Grinding errors, like accidents, do not merely happen, they have causes.

Work, machine and wheel are the definite, known quantities in the equation. Grinding troubles are usually due, therefore, to the variable unknowns, such as the condition of the grinding machine, skill of the operator in manipulating the machine, and even to the operator's psychological reaction.

It is the unknown quantities which require expensive time consuming experimentation. Often they are plainly visible to one who knows what to look for. But too often they are ignored, and a solution of a grinding problem is sought in a specially made wheel of special characteristics. Such a wheel will often produce a faultless grinding job even under the handicaps loaded upon it, but this special wheel will seldom do the job as efficiently as would a Standard wheel operated under proper and usually easily attainable conditions. The grinding faults given on pages 69 to 78 will explain how many a grinding problem can be solved without recourse to specially made wheels.

Cylindrical Grinding—Chatter

INDICATION	CAUSE	METHODS OF CORRECTION
Chatter marks—short, close and evenly spaced.	Loose wheel spindle bearings.	Reduce speed; tighten or refit bearings; lap spindle bearings; increase quantity or improve quality of oil; allow sufficient preliminary heating; take up thrust bearings.
Chatter marks—slightly longer and more widely spaced.	Wheel spindle sprung or out of round.	If warped, replace; if out of round, regrind and lap to new bushings.
Regularly spaced chatter marks.	General vibration.	Check alignment and couplings; be sure motor and spindle are in balance.
	Wrong work speed.	Determine speed at which vibration is at a miminum.
Regularly but widely spaced marks.	Uneven belt.	Plane belt to uniform thickness and width; have all sections of uniform pliability.
	Idlers loose or out of balance.	Rebush and lap to shaft; balance carefully.
Long, regularly spaced chatter marks forming a checkerboard pattern.	Wheel out of balance.	Rebalance carefully on own mounting; repeat after truing operation. If trouble persists run wheel without coolant to throw off excess water; store on side to prevent water from settling at lower edge of wheel.
	Wheel out of round.	True before and after balancing; true sides to face.
Chatter marks long and widely spaced; regular in pattern but may vary around body of work.	Backlash in drive gears.	Replace old gears or use belt drive; check lubricant.

CYLINDRICAL GRINDING—CHATTER (*continued*)

INDICATION	CAUSE	METHODS OF CORRECTION
Regular or irregular chatter marks.	Faulty thrust bearings.	Replace thrust bearings.
Regularly or irregular spaced chatter marks of any width but following one pattern.	Metal belt lacing on spindle drive.	Use endless belt.
Regularly spaced marks occurring more frequently than when caused by belt lacing.	Loose pulley on spindle.	Tighten pulley on spindle.
Chatter marks spaced synchronously with building vibration.	Building vibration.	If a heavy grinder—provide a separate foundation independent of the surrounding floor. If a light grinder—tighten or loosen anchor bolts. Vibration dampers often will help. Moving the machine to a better location is sometimes the best solution.
Chatter marks fairly long, wide and evenly spaced at wide intervals and generally discoloured; wheel glazed or loaded.	Wheel grading too hard.	Select softer grade, more open bond, or coarser grit.
Irregular chatter marks.	Work centres or work rests not true, or improperly lubricated.	Check fit of centres and rests; provide constant and even lubrication; on large jobs such as roll grinding, provide hold down clamps on necks and arrange for adequate lubrication.
General.	Dressing.	Use sharp diamond—rigidly held close to wheel and in the correct position.

Scratching of Work

Narrow and deep regular marks.	Wheel too coarse.	Use finer grit.
Wide irregular marks of varying depth.	Wheel too soft.	Use harder grading (*see* " Grading Effect on Wheel ").
Widely spaced spots on work.	Hard spots or glazed areas on wheel face.	Balance and true wheel; avoid getting oil on wheel face.
Uneven marks on work.	Whipping belt.	Take up belt.
Fine spiral or thread on work.	Faulty wheel dresser, or dresser in wrong position.	Replace cracked or broken diamonds; use slower dressing traverse; set tools at angles of 5 degrees down to 30 degrees side; turn diamond every third dressing; tighten holder or diamond; dress with less penetration; do not allow tool to dwell in contact with wheel; do not start dressing cuts on face—locate tool on face, but start cuts from edge; make final pass in dressing in opposite direction to grinding traverse; traverse diamond across face of wheel evenly; round off wheel edges—chamfering or dressing back is not sufficient.
	Faulty operation.	Prevent penetration of advancing or following edge of wheel by being careful to dress wheel face parallel to work; reduce wheel pressure; replace worn parts which permit swivelling of wheel head; provide additional steady-rests; reduce traverse in relation to work rotation; when making numerous passes, make slight change in traverse at each pass to break up pattern.

CYLINDRICAL GRINDING—LOADING OF WHEEL—(*continued*)

INDICATION	CAUSE	METHODS OF CORRECTION
Metal lodged on grains or in wheel pores.	Faulty dressing.	Use sharper dresser; dress faster; clean wheel after dressing.
	Faulty coolant.	Use more cleaner or thinner coolant.
	Faulty operation.	Manipulate to soften effect of wheel (*see* "Grading Effect of Wheel"); use less in-feed.
	Glazing of Wheel	
Shiny appearance; smooth feel.	Improper wheel.	Use coarser grit; softer bond; manipulate wheel to soften effect (*see* "Grading Effect on Wheel").
	Improper dressing.	Keep wheel sharp with sharp dresser; faster traverse; more tool penetration.
	Faulty coolant.	Use less oily coolant; use more coolant.
	Faulty operation.	Use greater in-feed (*see* "Grading Effect on Wheel").
	Gummy coolant.	Increase soda content if water if hard; do not use soluble oils in hard water.
	Inaccuracies in Work	
Work out of round.	Uneven pressure of driving points.	Provide cushion between points and work; place points equidistant from work axis.

	Driving points not parallel with axis.	True faceplate and pins.
Work out of parallel or tapered.	Faulty grinding machine.	Correct worn ways and setting of tail or head stocks; tighten spindle bearings.
	Improper dressing.	Make sure machine conditions are same at point of dressing as at point of grinding.
	Improper operation.	Do not permit wheel to pass off work at end of traverse, which causes taper at work ends; decrease pressure, which springs work; use harder wheel.
	Expansion of work.	Reduce temperature of work by using more coolant and lighter cuts; keep work out of draughts.
	Check Marks on Work	
Work shows check marks.	Improper wheel manipulation.	Prevent wheel from acting too hard (*see* "Grading Effect on Wheel"); do not force wheel into work; use larger and more even flow of coolant; prevent belt slippage.
	Burning of Work	
Work shows discoloration.	Improper wheel.	Use softer wheel or manipulate to get softer effect (*see* "Grading Effect on Wheel"); prevent glazing and loading; apply coolant before contacting wheel and work; use more coolant; prevent chatter.

CYLINDRICAL GRINDING—BURNING OF WORK—(*continued*)

INDICATION	CAUSE	METHODS OF CORRECTION
Work shows discoloration.	Faulty operation.	Bring wheel to work more gradually, use less in-feed; eliminate belt of wheel slippage; prevent possible stoppage of work.
Centreless Grinding		
Irregular light and dark spirals.	Stock.	Remove all oil from stock straightener; use detergent coolant.
	Dressing.	Dress regulating wheel at same angle as wheel setting, otherwise small diameter work may be bent while traversing, due to uneven pressure. If clearance angle is wanted—apply to grinding wheel.
Scratching (fine wheels).	Work support blade.	For ultra-finish grinding, bakelite work support blades are best.
Scratching (general).	Work support blade.	For soft steel use cast iron work support blades.
Periodic deflections of work.	Work support blade.	Reduce top angle. For large diameter work the blade angle should be less than when using the same length of blade for smaller diameter work.
Chatter.	Wheel too hard or too fine; loose on mount.	Change wheel; check mounting.

	Work support blade. Too sharp an angle, or not proper clamped.	Correct blade angle; tighten up.
Scoring.	Coolant.	Requires more lubricating qualities.
Spirals on work.	Wheel cutting too heavily on front or back, or cutting both front and back and not in centre of wheel.	Dress grinding wheel so that it cuts from front to within $\frac{1}{2}$ in. to 1 in. back of edge.
	Work support plates not parallel with work contact line on regulating wheel.	Line up guide plates with lining bar approximately same diameter as work being ground. If guides are parallel and wheel dressed correctly, increase regulating wheel housing angle $\frac{1}{2}$ degree more than regulating wheel truing device angle.
High centres, low ends on works.	Improper alignment of guides or regulating wheel angles.	Align guides and if still at fault decrease regulating wheel angle by $\frac{1}{4}$ degree steps until corrected.
Low centres on work, high ends.	Improper alignment of guides or regulating wheel angles.	Align guides and if still at fault increase regulating wheel angle by $\frac{1}{4}$ degree steps until corrected.
Work out of round.	Too heavy stock removal on roughing cuts.	First cut light, to round up work; then use heavier cuts.
	Too few passes on hardened work.	Increase number of passes, if necessary.
	Too near centre of wheels.	Raise centre height of work to one-half diameter of work above centre line of wheels.
	Wheel grade too hard.	See that copious supply of clean coolant is available at point of contact.
	Not enough coolant at point of contact.	As last resort use softer wheel grade.

CENTRELESS GRINDING (*continued*)

INDICATION	CAUSE	METHODS OF CORRECTION
Chatter.	Loose spindle bearings or other loose driving parts.	Lap spindle bearings.
	Too high above centre.	Decrease centre height.
	Too great angle on work rest blade.	Use 30 degrees blade angle, which is sufficient in 90 per cent. of cases.
Unable to straighten kinks out of shaftings.	Shafting not straightened in punch presses or other devices.	Straighten as close as possible; a centreless grinder is not a straightening machine.
	Failure to allow enough stock on work for grinding.	Allow grinding stock to equal from $2\frac{1}{2}$ to 3 times the amount of run out.
	Too great grinding pressures.	On first pass through grinder, take light cut at low wheel speed and high traverse rates.

Internal Grinding

Spindles.—High speed internal grinder spindles of the ball-bearing type are very sensitive to slight irregularities. Because of their special construction and special races and balls, it is best that repairs be made only by the spindle manufacturer. Lubrication of spindles is of great importance. Use only the lubricants recommended by the spindle manufacturer.

Machine Play.—Since both wheel and work heads may be of the swivelling type, they must be checked for play and anchorage.

Belts.—Internal grinder belts, with their high speed short centres and small diameter pulleys, must be frequently checked for oilness, wear and tightness, as slippage is an especially serious fault.

Dressing.—Faulty dressing is one of the most frequent causes of faulty grinding, short wheel life and poor finishes. Keep careful watch to prevent wear in the diamond holder bearings. Because of the small size of the wheels used in internal grinding, it is essential that the diamond be of proper size and maintained with a sharp point.

Wheel Characteristics.—Most internal wheels are less efficient than other wheels because of the extreme change in wheel diameter with no corresponding change in spindle speed. Often it is possible to increase wheel life by using a wheel of greater width. Due to the limitations of chip clearance in internal grinding, it is necessary to use coarse, open wheels.

Tapers in Straight Holes.—Be sure wheel head is parallel with table traverse; use softer wheel or increase work speed for softer effect; correct work or wheel head alignment; prevent gumminess of coolant; use lighter in-feed; be sure wheel is dressed parallel to table travel; use harder wheel.

Bell-Mouthing.—Reduce over-travel of wheel from hole.

Faulty Taper.—Be sure wheel is parallel to desired taper; eliminate backlash in headstock; harden or soften wheel as required (see " Grading Effect on Wheel ").

Wheel Breakage

Radial Break, three or more pieces.—Reduce wheel speed to rated speed. Correct improper mounting, such as: lack of blotting paper washers or pads, tight arbors, uneven flange pressure, dirt between flanges and wheel, prevent overheating due to lack of coolant, or excessive wheel pressure on work. Do not allow wheel to become jammed on work.

Radial Break, two pieces.—Prevent excessive side-strain.

Irregular Break.—Do not allow wheel to become jammed on work; prevent blows on wheel; don't use wheels that have been damaged in handling; examine wheel before using. Sound wheel by tapping.

General.—Do not use a wheel that is too tight on the arbor as wheel will break when started. Prevent excessive hammering action of wheel. Familiarize yourself with the provisions of the safety code governing use of grinding wheels—and observe the rules.

SECTION SIX

Finishing Operations of Surface Finish

Honing

THIS process has been considerably improved during the past years, and is in extensive use for the finishing of internal work such as cylinder bores of motor engines; although the process uses abrasive stones it should not be confused with internal grinding.

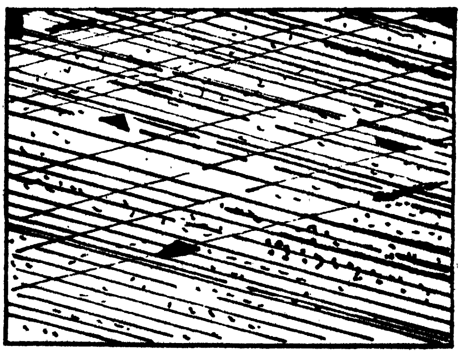


FIG. 36.—Sketch of cross hatch surface.

The hone is used to carry between three and eight abrasive blocks, which may be expanded, and the finish is produced by these blocks describing a spiral path on a vertical axis, thus producing a cross hatched finish as shown in FIG. 36.

Because of the large area of abrasive surface the pressure per square inch is much less than that of grinding, being only from 50 to 200 lb.

Honing causes a dimensional change in the workpiece by reason of the pressure which is applied at some speed and the heat which is generated in the work surface, although the rise is only between 100°F. and 300°F., thus creating surface ductility to a depth of between ·0001 to ·001 inch.

Honing is in general a faster operation than lapping, but by no means as fast as grinding either for stock removal on in cutting time. The process is not confined to internal work: it can be satisfactorily used for finishing flanges and other surfaces where a pressure tight joint is required.

The allowance for stock removal varies between ·002 in. and ·007 in. A lubricant of oil-paraffin mixture is used for washing away the particles of metal and dislodged grit.

In recent years honing has been developed until, by means of hydraulic honing equipment which allows proper control of unit pressure by means of balanced hydraulic actuation, greater control of surface character and finish has been possible at a high production rate.

Honing is not confined only to the finishing of cast-iron cylinder bores, but is now used for soft and hard style steels, and the war-time production has assisted the development of honing machines, tools and abrasives to meet industrial demands.

Within the aircraft industry the pin-holes of articulated rods have had machining scratches removed by a honing process to ensure the maximum bearing area of the pin being utilized. The use of honing has produced holes free from scratches in a position where such scratches might well develop into a fracture under the high pressure at which the pins have to operate.

The production of gun bores has increased the efficiency of the bore by being honed, and the application of co-directional honing has been further developed during the man[illegible] and finishing of gun parts.

Co-directional honing has a non-rotating motion exc[illegible] the ends of the stroke, and a surface produced by this method is a series of microscopic lines parallel to the piston travel, in the case of bores.

One important development in this equipment has advanced into the field of heavy stock removal under minimum conditions of structural disturbance within the metal being processed, thus giving greater dimensional accuracy and higher quality surface finish.

The process may be considered to give four results: (1) It generates surface character and (2) size accurately; (3) gives a high degree of surface smoothness, and (4) removes a certain amount of stock.

With regard to the working of honing machines, the control of pressure between the bore and abrasive is of particular importance. This pressure may be applied mechanically or hydraulically, dependent on the type of machine; but it is generally realized that the pressure is a low starting pressure gradually increasing and then diminishing, and in mechanically operated hones this cycle may be largely dependent upon the skill of the operator.

With regard to the actual measurement of the surface after honing by production methods, this varies from 1·5 micro-inches to 5 micro-inches dependent on the type of surface and hardness of the metal, while the accuracy of small bores may be held to tolerances of plus/minus ·0005 in.

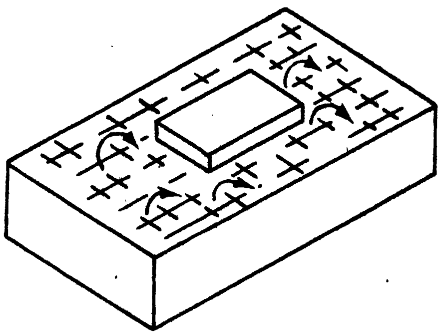


FIG. 37.—Lapping (abrasive process).

The process is usually operated in two parts, the first being [illegible]out by abrasive stones of around 150 grit, and the second [illegible]ing which uses around a 500 grit, thereby producing a m[illegible]-like finish surface, but at the same time taking care of the need for indentations for the correct working of the future oil film.

Lapping

Lapping is regarded as the oldest method of obtaining a fine surface and is extensively used in the engineering world, especially in the toolroom, for the finishing of gauge blocks and flats for checking production parts; it is also used for the finishing of precious stones, and for optical work, so it may be considered as a process requiring great skill on the part of the workman, and is a slow and rather tedious method of producing the desired surface.

The finish obtained is a series of minute scratches which are measurable with a surface meter, and the graph produced shows that the scratch pitch is exceedingly fine, thus ensuring the good bearing surface, as the scratches do not occupy anything like as much of the total surface area as is the case in the three previous processes.

If the running surfaces, such as a hydraulic piston and a bore, are lapped together the bearing area is considerable, thereby ensuring a close fit.

A lapping allowance of about ·0002 in. is required for hand lapping of first class surfaces.

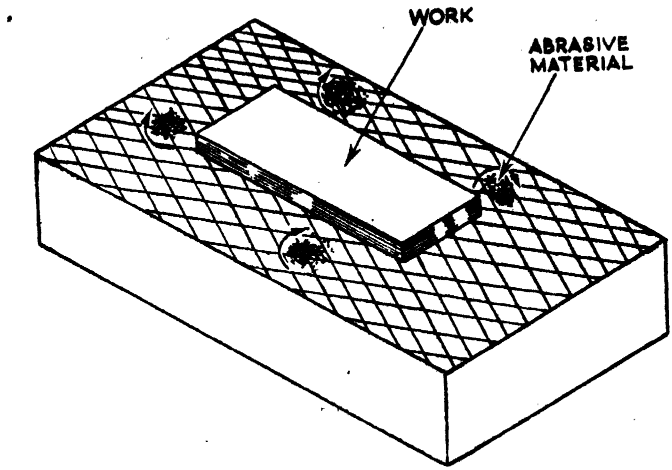


FIG. 38.—Toolroom lap (heavy duty).

Lapping machines have recently been introduced for use of ring gauges and jig bushes; such a machine comprises a high speed spindle driven by an electric motor, on which the laps are carried. FIG. 38 shows [redacted] duty toolroom lap, which is of cast iron impregnated [redacted] lapping material which is a loose powdered [redacted] such carriers as oil or grease.

For toolroom purposes, such as [redacted] of gauges and gauge blocks, lapping may be considered [redacted] hand operation and may in consequence produce very high quality finishes in small quantities.

The operator's interest and patience is indicated clearly in the resulting workpiece.

The surface of a workpiece prior to lapping should always be ground and should be geometrically and dimensionally correct. Lapping then induces a desired finish.

The chip-face of cemented-carbide tools is ultra-smooth and finished by hand lapping.

Superfinishing

In 1933 considerable interest was aroused within the automobile industry by experiments which were being carried out to decide reasons for the scoring and ultimate breakdown of engine big-end bearings. Many theories were put forward but strangely enough little notice seems to have been taken of the actual surface profile of the working surfaces, although this may have been due to a lack of equipment for surface examination. Because of severe Brinelling of the working surfaces of the hubs of motor vehicle wheels during long transportation on railways, the Chrysler Corporation of America evolved a method of surface finish which differed in a number of ways from any previously known method, and by extending this to other bearings than those in the hubs, produced a method known as " Superfinishing ".

Consider just how easily such a smooth surface is obtained by natural means. A pebble on the seashore is frequently spherical and a very smooth surface is obtained by the constant action of the sea washing it against the fine particles of sand. Consider this natural operation in the light of a mathematical method.

If the workpiece (pebble) is revolved against fine grains (sand) at a slow speed with a suitable lubricant it is possible that a very smooth surface will result, and if the process were scientifically applied there need be no appreciable change in the dimensions of the workpiece. This, in effect, is the superfinish theory, coupled with a suitable oil wedging action when the surface is smooth.

By reviewing SECTION 4 it [redacted]ed that the commercial methods describe[redacted]hich are undesirable to the surfac[redacted]disturbed and fragmented by the action [redacted]the crystalline structure, and (2) heat is generate[redacted]the surface layer of the metal.

By the Superfinishing method, however, this fragmented metal is removed without heat being generated, and the principle is as follows:

The stock removing tool used in superfinishing is a suitable shape of bonded abrasive usually called the "stone". In work on cylindrical parts, this shape is almost always a square stone, the working surface of which is curved to the same radius as the surface being superfinished. The face of this stone is held in contact with the work by spring or hydraulic pressure of 15 to 30 lb. per sq. inch. As the part being superfinished is rotated, the stone is given an endwise oscillation,

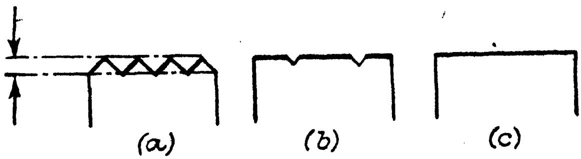


FIG. 39.—Sketch of surface finishes. (*a*) Normal turned surface. (*b*) Superfinished surface. (*c*) Theoretical ideal surface.

which results in a grit path of a continuous curve that is alternated in direction several hundred times a minute.

The oscillating movement imparted to the stone is responsible for the removal of such surface patterns as grinding ridges.

The endwise movement is at a rate of 350 to 900 complete cycles per minute. The oscillation is of sufficient length that several ridges of almost any sort of surface finish will be passed over by each stroke. Their removal is thus much easier than it would be from the same direction in which the defects were

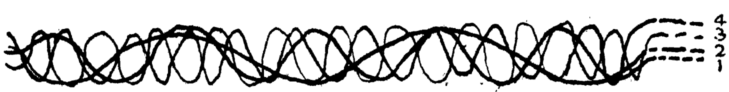


FIG. 40.—One of the many hundreds of designs which the stone may use by increasing or decreasing the work revolutions in relation to the stone motions.

produced. Yet this motion is short enough to permit rapid reversal in direction, with a very beneficial result to the speed of the process and to the quality of the surface produced.

An abrasive grit is essentially a stock removing tool, and as it moves through the metal of the surface it piles up a chip which is liable to become larger as the same face of the grit continues to cut. Such "loads" are the cause of the production of deep scratches if they are allowed to form. By oscillating the stone, the direction of the cut is changed rapidly, so that loads of consequential size seldom accumulate. Not only is this true, but the metal is thus more efficiently removed by a shearing cut, and the grit points stay sharp longer because more of their angles are used. These are some of the reasons why superfinished surfaces are produced in so short a time.

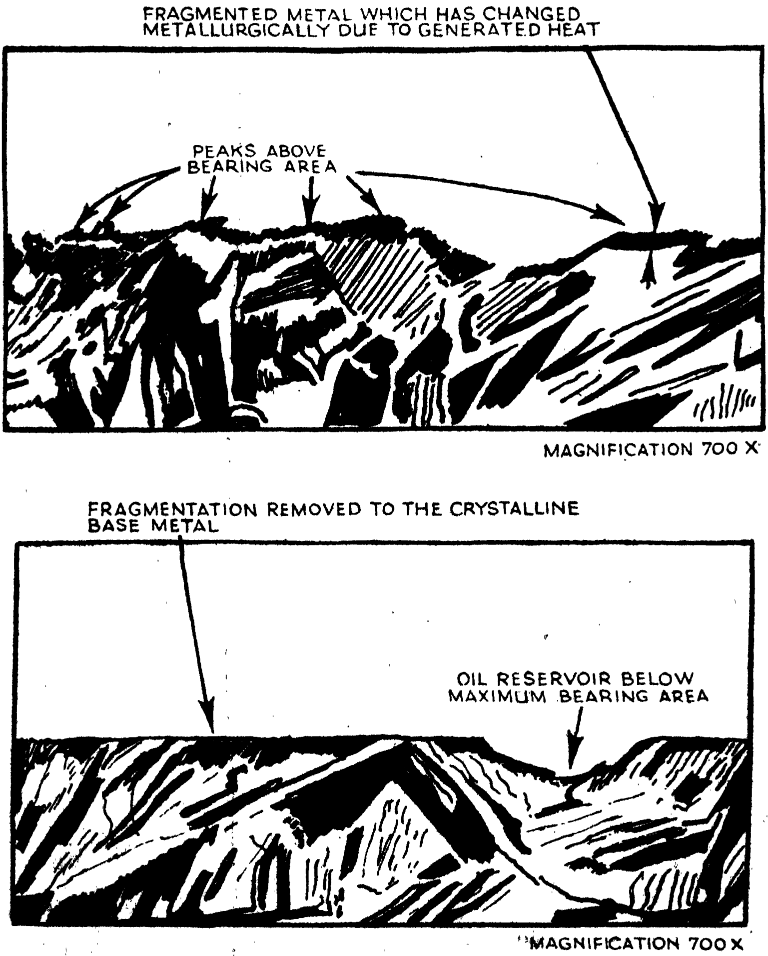


FIG. 41.—By comparing these two profiles, one the result of a grinding operation, the other a result of superfinishing, the value of removing the fragmented material is shown.

After the grit point has traced its path once around the circumference of the part, it will never again exactly follow the same path; instead, the curves cross each other, forming a "cross hatch". The combined effect of the 360,000 grits in a single square inch of the face of a 600-mesh stone, and the oscillation producing this "cross hatch" result in a surface with none of the defects due to a single direction of stock removal. A superfinished surface is one having the same characteristics in every direction. No pattern such as grinding ridges can remain after the application of this process.

During the operation the stone is flooded with a lubricant of light viscosity. The defective layer of metal is thus removed by the scrubbing action of the abrasive as the part is rotated. The speed of this rotation is at a low rate, averaging no more than 60 surface feet per minute.

Lubricant

The comparatively low speeds of the component and the abrasive stone, as well as the scientific application of the process, render the use of a coolant unnecessary, but a lubricant must be introduced to wash away all traces of fine particles of fragmented metal and dislodged grit, at the same time bringing the hydrodynamic oil wedge principle into operation at the correct moment.

Care must be taken in the choice of a mixture to form the lubricant, and for the majority of operations a mixture of mineral oil of good quality and fairly heavy viscosity with paraffin is satisfactory. The mixture should have about 15 per cent. mineral oil to 85 per cent paraffin.

The obtaining of a desired surface now becomes a matter of mathematical calculation based on the hydrodynamic laws, and the formula is:

$\frac{ZN}{P}$ where Z = viscosity of the lubricant in centipoises,
N = surface speed in feet per minute,
and P = total load acting on workpiece in lb.
= pressure on projected area in lb. per square inch.

The ability of the lubricant to create a fluid film sufficient to carry a load is due in the main to the building up of a pressure during the motion of the fluid. It follows that, to maintain this film, the surfaces which are separated by it must be in such a position that the pressure of the fluid exactly balances the load. To set up the operation for obtaining a fine surface finish, a constant speed N with a light pressure P is required and if, after processing, scratch marks are still visible, or, in other words, if all the fragmentation has not been removed, then *P* must be increased.

Too much *P* will cause the lubricant to gush away from the abrasive stone, and pressure must be reduced for surface finish only, but may be used for geometrical correction of the workpiece.

The following table shows a comparison of machining and finishing methods:

Commercial Methods	Fine Surfacing
High tool speed High tool pressure,	Low tool (abrasive) speed Low pressure,
resulting in:	*resulting in:*
High temperature of surface,	No surface temperature,
requiring:	*requiring:*
Use of a coolant. Not more than 3 motions.	Use of a lubricant. Up to 10 motions.

From a purely surface point of view results of the processes may be summarized as follows:

Scratches above bearing surfaces	Scratches below bearing surfaces, resulting in a crystalline bearing surface.
High friction to lubricated surfaces.	Low friction to lubricated surfaces.

The removal of the surface fragmentation takes place in such a minute state by reason of the light pressure of the abrasive stone that oxidization of some metals takes place instantly, thus producing a black stain in the lubricating fluid.

Thus it will be seen that both the theory and practice of obtaining a high quality surface by the superfinishing process differs from any other method because the surface is produced under the same laws which govern the lubrication of a bearing.

Cutting Tools

In Section 5 the problem of cutting tool edges has been dealt with and several points have been stressed, especially when grinding the edges during resharpening.

Grinding methods tend to produce a coarse surface with high ridges which are detrimental to efficient cutting, and which tend to allow minute welding to take place between the tool and the chips.

The production of a smooth tool face improves the cutting operation for several reasons. The chip pressure will be uniformly distributed over the entire cutting surface. The cutting fluid or coolant will be more evenly distributed. Friction between the chip and the top tool face, in the case of lathe tools, will be reduced.

And now to turn to practical application of superfinishing.

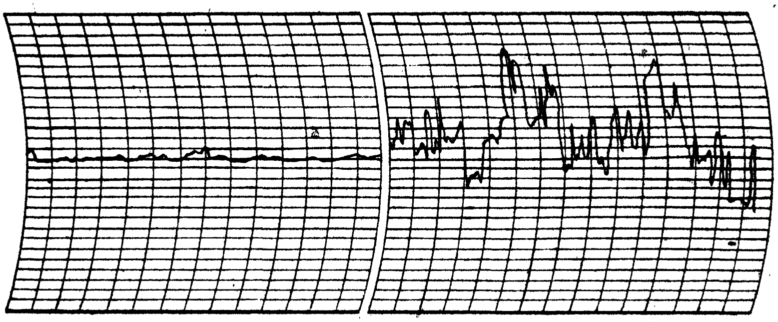


FIG. 42.

Graph of superfinished journal; magnification V 20,000, H. 150, average reading 1·5 micro-inches.

Graph of ground journal; magnification V 20,000, H. 150, average reading 18·5 micro-inches.

Messrs. Hayward, Tyler & Company Limited, makers of a wet motor pump, have supplied the following information on their use of the superfinishing process.

First the type of work which has to be performed by the wet motor pump may be considered.

It is designed to raise water from considerable depths in the simplest and most efficient way, to be easy and relatively inexpensive to install and cheap to run. The motor and pump are coupled together and operate at the bottom of the well, and no attempt is made to keep the water out of the motor. It is in fact cooled and lubricated by the water in which it is immersed and which circulates vigorously between the rotor and stator, and throughout the windings, thus making use of its environment.

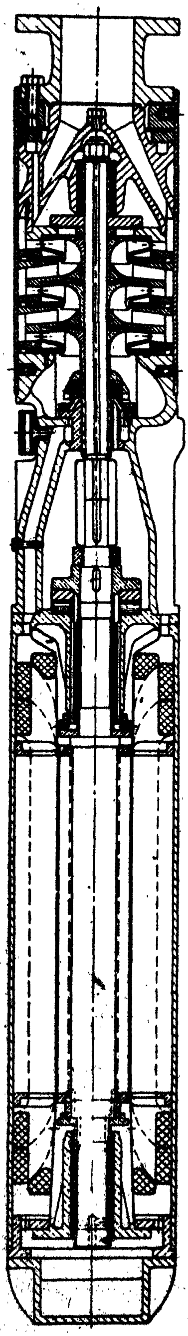


FIG. 43.—Sectional pump and motor in which all bearing surfaces are superfinished.

The bearings which are used throughout the pump and motor are water lubricated, thus ensuring freedom from oil or grease in the water.

The pump bearings are of the plain formal type, the housing being lined with a fabric material bush, leaded bronze or other material suited to water lubrication.

The motor bearings are similar.

In water lubrication the film is thin because of the low viscosity of water. It follows that, unless surfaces are truly smooth the peaks left by a grinding operation will come into contact during the running-in period.

By using the superfinishing process full film lubrication is ensured from the start, and the comparison graphs show the profiles of a journal sleeve after grinding and also after super finishing. This results in all journal sleeves used in producing the wet motor pump being fine surface finished.

In discussing the process, in a letter to the author, Messrs. Hayward Tyler point out that the water film is approximately one-tenth as thick as the corresponding oil film, and for this reason, if true film lubrication is to be achieved, surface irregularities should not be of a magnitude comparable with that of the film thickness.

On a superfinish journal, no change in the surface conditions is apparent after many hundreds of hours of running in clean water.

Since the carrying capacity of the bearing varies inversely as the square of the clearance ratio, with plain ground surfaces, the surface condition of fragmentation running in to a smooth finish caused undesirably large clearances, with a corresponding loss of load-carrying capacity and reduction in the factor of safety of the bearings.

With superfinished surfaces which are in a satisfactory running condition with the designed working clearances the factor of safety is correspondingly increased.

A correctly conditioned surface of correct geometry has shown during tests carried out by Messrs. Hayward Tyler to be able to carry loads of over 1,600 lb. per sq. inch on a water film at an average linear speed of 60 ft. per second.

This proves beyond doubt that a satisfactory (but not necessarily a mirror finish) surface can be obtained by fine surface processes and the above are in effect the practical application of superfinish theories.

Turning to machines for superfinishing, these have been developed since 1937 and now have a considerable share in producing fine surfaces.

The special purpose equipment includes machines for engine crankshaft finishing which operate on six big-end bearing journals and four main bearings journals simultaneously. Centreless type machines, for piston surface finishing, brake drum finishing machines, valve stem surface production accommodating thirty-three valves at once, camshaft bearing and cam contour finishing machines, continuous type machines for finishing tappet heads showing production figures up to 1,200 per hour, all indicate the range of equipment available and types of surfaces which may be produced commercially.

Success has been obtained by machines which process tapered rolling bearing rings, both inner and outer of all sizes.

With all the improvements in machining methods, lubricants and other factors affecting working surfaces, the actual surface was a factor which had not, until recently, kept pace with modern progress.

Even now, engineers have to develop ideas which will lead to practical advances in the mechanical perfection of surfaces on a commercial scale.

SECTION SEVEN

The Measurement of Surfaces

AFTER reading the previous section many questions will enter the reader's mind regarding methods employed in the measuring of surface to a high degree of accuracy, and in recent years the importance of knowing the condition of a surface of machined parts such as have previously been considered has been fully realized.

By the development of the science of surface finish a new standard of measurement has been made necessary in order to express the varying qualities of finish produced by the various methods of machining.

The general standard of measurement up to about fifty-five years ago was the steel rule graduated in 64ths of an inch, and the method of transferring any dimensions was by the use of internal and external calipers.

About 1895 the micrometer was introduced, creating standards of measurement to a thousandth of an inch, with a corresponding increase in accurate dimensional reproduction.

The vernier introduced further dimensional accuracy.

Surface finish is the most forward stride, since it demands the universal use of the micro-inch or one millionth of an inch, and this measurement is not confined to research and laboratory use, but is used as a standard in the inspection department and the machine shop.

Planning and production departments are concerned in general with an agreed standard of finish being maintained, but the checking of component surfaces must not be a long job.

It has been possible to determine accurately the structure and dimensions of a component, but the surface is often a matter of chance rather than mathematical accuracy.

Any machined surface is made up of a vast quantity of irregularities caused by the cutting or abrasive tool action in removing a portion of the structure of the metal, but at the same time leaving behind a pattern. This pattern completely covers the machined surface, and determines its appearance and the suitability for its purpose.

The three groups of surface irregularities are: (1) roughness, or micro (2) waviness, or macro and (3) surface flaws.

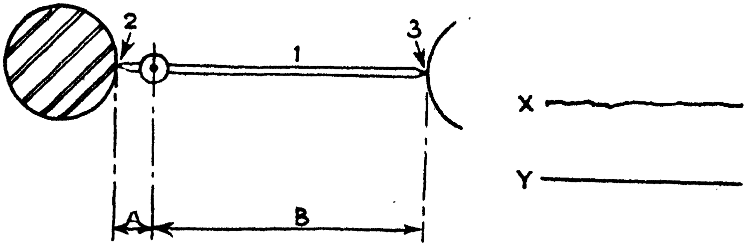


FIG. 44.—Diagram of method of surface roughness measurement. The recording arm (1) is fitted with a probe point (2) which explores the surface and a pen point (3) which records the profile. The ratio A–B may be up to 20 : 1.

(1) *Roughness.*—This is made up of random irregularities, very closely spaced, and imposed on a wavy surface.

(2) *Waviness.*—A surface deviation consisting of recurrent irregularities often in the form of waves, the helix of which is far greater than the depth.

(3) *Flaws.*—Irregularities which occur at infrequent and random intervals on the surface.

A very early type of surface measuring instrument is shown diagrammatically in FIG. 44. Here is illustrated a piece of rough stock which has to be machined. Starting at point A and developing a line in circumference in a straight path, a line is produced as X. Repeating this method after the stock has been machined will produce a line similar to Y. Notice the difference in the irregularities produced in the two lines.

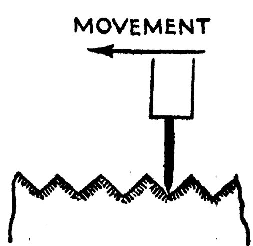


FIG. 45.—Sketch of stylus in surface irregularities.

Such lines or records, described throughout this book as graphs, may be obtained by a lever of predetermined length, one end of which has a suitable edge or point which bears on the stock, whilst the other end has a pencil point which bears lightly on a piece of paper. The paper travels at the same speed as the workpiece and in the direction of the axis of the work.

The unevenness of the surface raises or lowers the pencil point and as the ratio between the knife edge (2) and the pencil point (3) is high, the variations of the surface shown on the paper are correspondingly magnified.

By utilizing the above simple method in conjunction with the unit of measurement (micro-inch), surface meters have been developed and produced proficient in every respect to enable accurate recordings to be obtained of the actual profile of the surface.

Some instruments measure the surface by means of a tracer point, which may be a pyramidal pointed diamond, traversing the surface in a straight line. During its traverse, this point explores the irregularities, and the movements it makes are magnified and recorded in various ways according to the type of surface meter.

Practically all surface recording instruments so far developed have taken the surface micro into account while ignoring the surface macro.

One of the most important factors which affects the ultimate surface is the series of defects under the heading of waviness or surface macro.

In the following descriptions of measuring instruments it should be noted that the author holds no brief for any particular method, but it should be remembered that it is because of research and investigation that equipment at a reasonable cost is available to all inspection departments and machine shops. It is hoped that the following remarks will assist in a rapid development of a method of surface measurements for general use.

Regardless of the methods used in actually carrying out the measurements a definite standard is required on the basis of existing data.

Two methods of observing the surface profile can be used, one at right angles to the direction of machining, and the other parallel.

Observation in plan view either by looking straight down or at an angle, shows the number of scratches, their width and length.

In making up the surface analysis the metallurgical composition of the surface layers should be noticed, and also how the physical properties of the surface layers affect the final surface specification.

The final analysis can include mechanical methods of measurement such as data on wear, friction and comparison, as well as physical methods, profile measurement, microscopic examination, chemical analysis, electron defraction grouping, and so on.

In considering the types of equipment available it is necessary first to know what is actually required, and the present data indicate that the following are the five main groups:

Group 1.—Measurements to determine that the surface is smooth enough for its purpose.

Group 2.—To ensure that the surface is not too smooth for its purpose.

Group 3.—To eliminate guesswork in the production of surfaces, and thereby reduce the cost of production by the elimination of unnecessary machining operations.

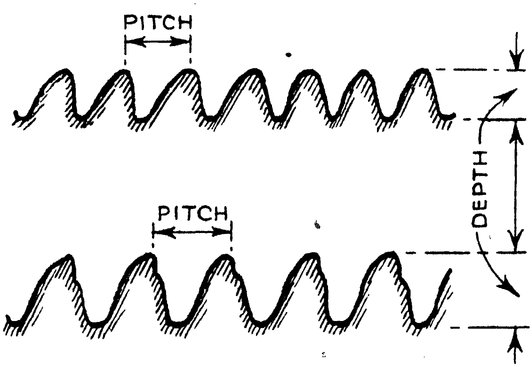


FIG. 46.—Profile records of feed and depth of cut.

Group 4.—To control intermediate finishing operations, especially in the case of honing after grinding.

Group 5.—To assist in the controlling of surface irregularities which may lower the fatigue strength of the part.

In the micro surface (roughness) measurement equipment the general practice is the movement of a stylus over a limited distance of the surface, and the resulting line produced must be magnified to be of any practical value. Such magnification may be either physical or accompanied by either light waves or electrical circuits.

By either of these methods a direct rating cannot be obtained, but a picture of the profile in the form of a graph is produced.

The vertical and horizontal magnification must be known, and the roughness shown on the graph is measured in relation to the known magnification.

To enable the stylus point to measure to one micro-inch it is necessary that it shall be sufficiently sharp so as to reach the bottom of all the irregularities, while the pressure between the point and surface must be small enough to prevent damage to either.

By examining the graphs in FIG. 46, which are profiles of the fine surface texture or micro, it will be noticed that they are in effect profiles made up by the combination of the cutting tool point in relation to the feed of the machine, the depth of the cut, and the speed of the workpiece. The maximum pitch of

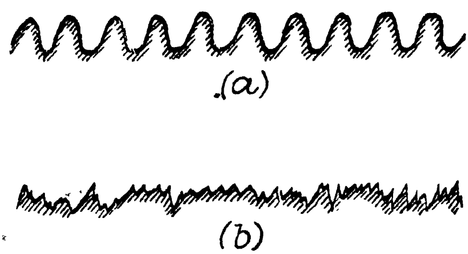


FIG. 47.—Comparison of (a) turned surface (b) ground surface.

the surface irregularities actually corresponds to the feed of the tool along the workpiece, thus forming in effect a very fine thread.

Examination of a ground surface profile (FIG. 47) does not indicate any of the above factors, because the nature of the application of the cutting action is not regular.

Consideration may now be given to three well-known surface roughness recording instruments, the first of American origin, and the second and third of English.

The Profilometer

The Profilometer was developed and is manufactured by the Physicist Research Company of the U.S.A. and consists of three units: (1) the Tracer, which is an electro-magnetic pick-up; (2) the Amplifier; and (3) the Meter.

The tracer is provided with a diamond tip which, when in use, is held in contact with the surface by a light spring pressure.

As the diamond point rises and falls with the irregularities of the surface under inspection, a coil moves in a magnetic field thus generating a small voltage which varies according to the displacement.

This varying voltage is amplified by means of a vaccum tube amplifier and is measured by means of a meter. The meter is calibrated in micro-inches, thus giving a direct reading.

The instrument may be had either as a portable battery operated unit, or to work from A.C. current mains.

One of the accessories available is a mechanically operated tracer which moves the tracer point over the component surface and ensures smooth strokes and quick, even reversals. This is used for mass production inspection, and the stroke length is variable between $\frac{1}{16}$ in. and $2\frac{3}{4}$ in.

Another interesting fixture is that designed to measure the surface roughness of piston rings on a quantity basis.

Tomlinson Surface Finish Recorder

The instrument was designed by the late Dr. G. A. Tomlinson at the National Physical Laboratory for measuring the micro-texture of machined surfaces. It is entirely mechanical in operation and the fine surface irregularities are recorded on a smoked glass plate. The record on the smoked plate is then magnified optically and examined directly at the screen of a projector.

The mechanical system, as shown diagrammatically in FIG. 48, consists of a lapped steel needle *A*, attached to the underside of the frame *B* by a flexible steel strip *C*. Attached to the lower end of this needle is the exploring probe which consists of a pyramidal pointed diamond with a tip radius of about ·0001 in. Two fixed lapped steel needles *D* and *E* are located in the frame *B*, and between these and the floating needle *A* a fourth needle *F* is held in a horizontal position by the tension of the spring *G*. Attached to the rolling needle *F* is a light steel strip lever *H* carrying at its free end a fine needle point *h*, which contacts the smoked glass plate. Hence as the exploring probe rises and falls, due to the surface irregularities, its movement is magnified at the scribing point in the ratio of the length of the lever *H* to the diameter of the rolling needle *F*.

The frame of the instrument is in two parts, *B* and *J*, connected by a hinge strip *K*. The polished steel skid *L* is brought into contact with the surface being tested by means of the controlling screw *M*, which rotates the frame *B* about *K*. At this stage the exploring probe is not in contact with the surface, but can be gently brought into contact by flexure of the skid. The amount of movement of the skid relative to the frame *B* is controlled by the screw *N*.

The movement along the surface is obtained by the rotation of the screw *O*, which is turned at a uniform slow rate by an independent motor drive through suitable reduction gearing.

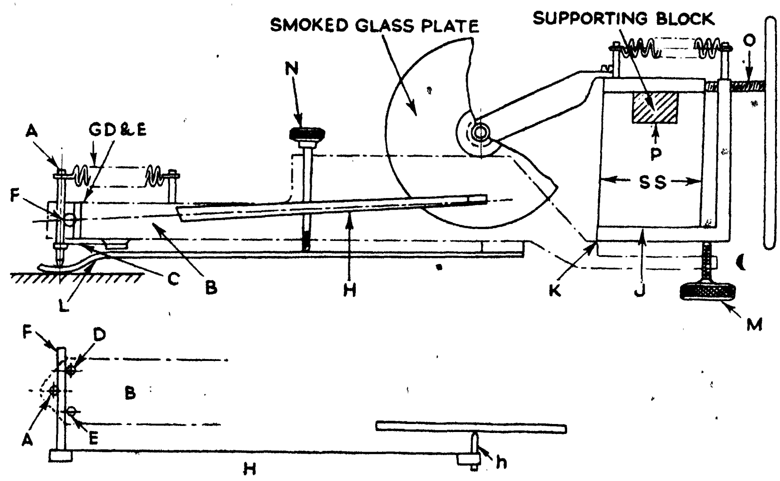


FIG. 48.—Tomlinson surface recorder.

This action imparts a linear motion to the back part of the frame *J*, which is slung by two steel strips *SS* from the supporting block *P*. The length of horizontal traverse of the recorder is about ·1 in.

It has been found that a vertical magnification of 10,000, i.e. 100 mechanical × 100 optical is in general sufficient to show quite clearly the fine surface irregularities due to different machining processes. All instruments of this design now made commercially use a *vertical mechanical magnification* of 100, i.e. the diameter of the rolling needle *F* is ·04 in. and the length of the lever is 4 in.

"Talysurf" Surface Roughness Measuring Instrument

The "Talysurf" Surface Roughness Measuring Instrument is a stylus type of instrument for measuring the roughness of surfaces.

A pick-up unit having a sharply pointed stylus is traversed across the surface by means of a motorized driving unit. The up and down movements of the stylus as it rides over the surface are converted into a corresponding electric current which is amplified and then applied to measuring instruments, providing:

(*a*) A graph drawn on paper, representing the geometrical shape of a cross-section of the surface undulations.

(*b*) A number shown by scale and pointer representing the average value of the undulations.

The magnification of the height of the undulations can be varied in steps over a very wide range. The standard self-contained magnifications are from 2,000 to 40,000, but by means of accessories the range can be extended down to 400 and up to 100,000. In the direction along the length of the surface, the normal magnification is 200.

The diamond measuring stylus has a radius at the tip of ·0001 in., which is small enough to ensure that even the deepest scratches are properly reproduced. It rests on the surface with a pressure of about ·1 gramme, which is light enough to ensure that the shape of even the softest metallic surface is not altered by the passage of the stylus.

The standard pick-up will measure the roughness of external flat and cylindrical surfaces, and will enter $\frac{3}{8}$ in. diameter holes to a depth of $\frac{1}{2}$ in., 1 in. diameter holes to a depth of 6in., and 4 in. to a depth of 8 in.

Accessories are available for the measurement of deeper holes, of surfaces between cheeks, like those of a crankshaft, of gear teeth, of ball and roller races and for the measurement of waviness and chatter.

Whatever type of surface meter is produced one of its chief characteristics must be an ability to measure the surfaces of a variety of shapes of workpieces.

Considering the practical results which may be expected from the various machining operations (such results being the product of a surface meter record), the following table constitutes a good average.

Turning	Diamond Tool	3 — 20 micro-inches
	Carbide Tipped	5 — 60 ,, ,,
Grinding	Production	8 — 120 ,, ,,
	Toolroom	4 — 8 ,, ,,
	Fine Ground	3 — 6 ,, ,,

Honing	2 — 40 micro-inches
Lapping	1 — 5 ,, ,,
Scraped by Hand	Approx. 25 ,, ,,
Superfinishing	·7 — 2 ,, ,,
Fine Surfacing	·7 — 2 ,, ,,

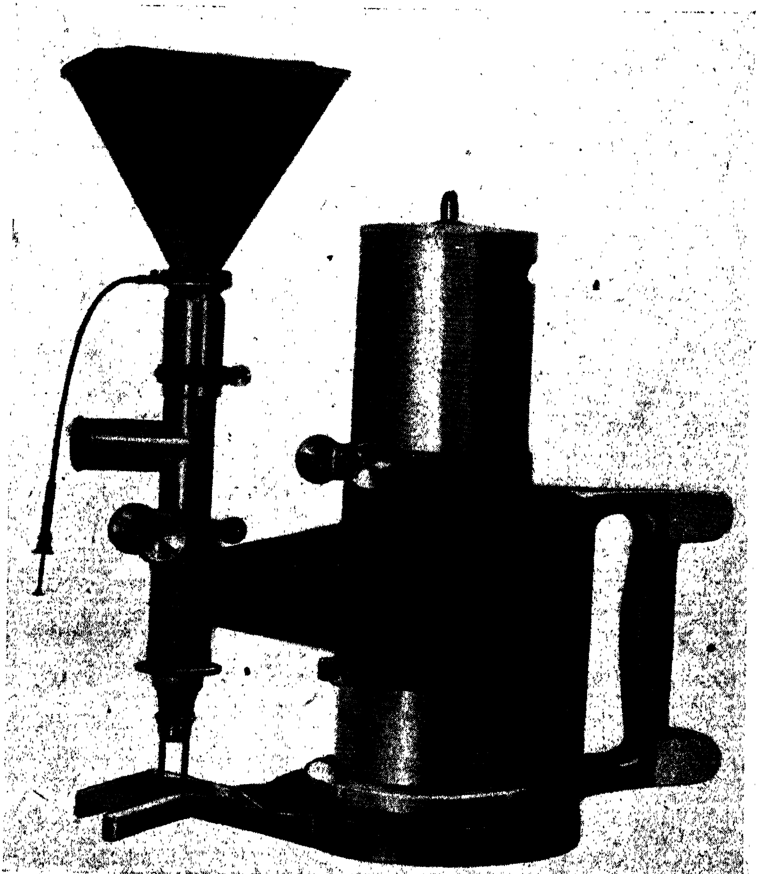


FIG. 49.—The P.V.E. surface finish measuring instrument for visual use with photographic attachment.

The accuracy of measuring micro-roughness of a surface with the recording instruments so far mentioned is limited by the radius of the exploring tracer point, which cannot be made less than ·0001 in. owing to the pressure of the point when in contact with the workpiece.

A rather different approach to the problem has been made by Mr. J. F. Kayser of Gillette Industries Limited, who considered the interference method of examining the surfaces of external parts. The method has been further developed by the National Physical Laboratory for the examination of flat surfaces, and early in 1945 Messrs. Pitter Gauge and Precision Tool Company Limited further developed a portable optical instrument, as shown in FIG. 49, which incorporates in one unit a light source, an optical system and reference lens, by means of which use is made of interference fringes of light for producing a series of bands, which follow exactly the minute differences present upon the surface under test, these bands being, in effect, a number of highly magnified (although distorted) pictures of the surface contours. With this method absolute accuracy of surface measurement is assured, there being no possibility of errors due to mechanical defects, or electrical faults, because the series of bands are themselves self-calibrating, the distance between each band depending upon the wavelength of the light being used, this dimension being practically constant for a given type of illumination under all conditions.

Consequently, although the overall magnification can be varied as required, the depth of surface finish may be immediately measured without reference to the variations, as the distance apart of the bands will always represent the same dimension.

The interference fringes are produced by means of a "reference" lens, the brightest and clearest fringes for highly reflective surfaces being obtained when the reference lens is coated on the side nearest the specimen under test with a reflective coating. This coating is not required, however, when examining glass or duller articles, and the coating, to some extent, prevents a clear view of scratches, etc., which may be superimposed upon the background. Both coated and uncoated lenses are therefore supplied, so that the user may have the most appropriate lens for any particular circumstances. It is recommended, however, that the coated lens be used wherever possible for photographic work, although for ground finishes the uncoated lens will give the best results, owing to the great difference between the reflecting powers of ground specimens and coated lenses.

The illuminating source used is a "sodium vapour" lamp, which emits light of a wavelength of 5,896 A.U., resulting in spacing between bands for practical purposes of ·000012 in.

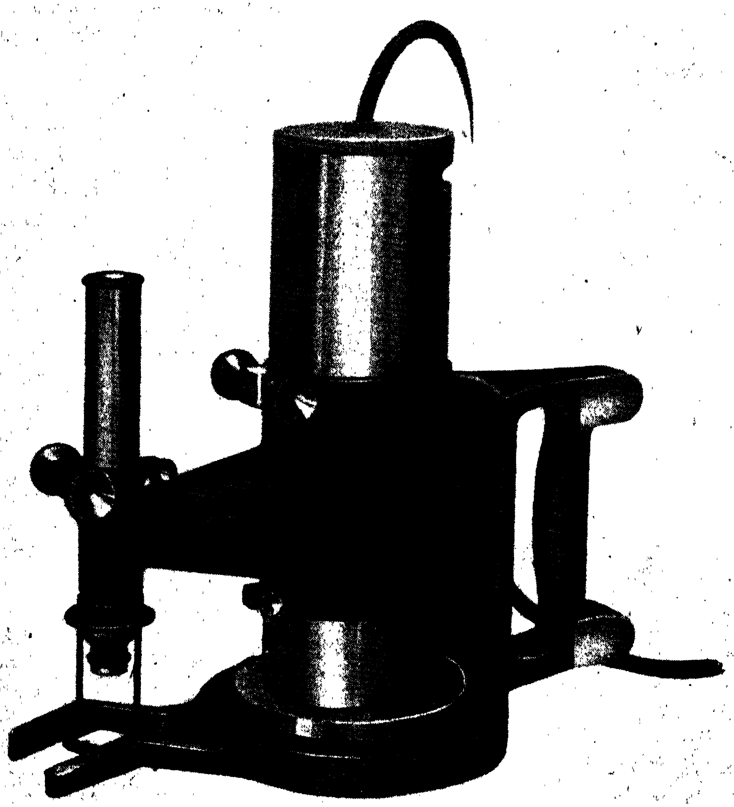


FIG. 50.—The P.V.E. surface finish measuring instrument for visual use only.

Sodium vapour lamps give off considerable heat whilst running but the lamp-house has been so devised that the heat is dispersed without affecting the instrument, and, after several hours working, practically no increase in temperature is detectable at the eye-piece, whilst the outside of the lamp-house feels only slightly warm to the touch.

Two variations of the instrument are being made at the present time, one for visual operation only and one for visual operation with photographic attachment for the making of permanent records of the surface under test. The instrument being quite light and comparatively small, may be "taken to the job" and one of the great advantages of the P.V.E. Surface Analyser is that, for large shafts, rolls or flat surfaces, the instrument may be stood or rested upon the article under examination. During the machining processes the analyser may be used for taking periodic checks until the required surface is

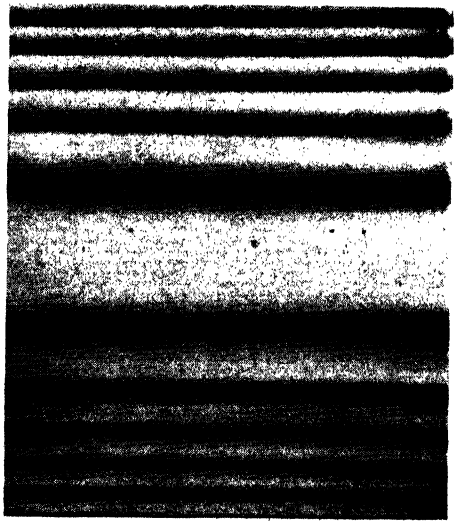


FIG. 51.—Finish of P.V.E. toolmakers flat showing no measurable deviation from a truly smooth surface.

obtained, when a photograph may be taken for record purposes, or as a guarantee that the part is to specification. The instrument will also just as readily deal with smaller components, which can be laid upon an anvil or vee-block, beneath the reference lens.

This instrument may be used for the checking of surface finish of convex, concave and flat surfaces, by means of the various special reference lenses provided.

Surface Standards

It has already been shown that to attain some measurement a standard must be introduced in order that such a measurement may come into general circulation.

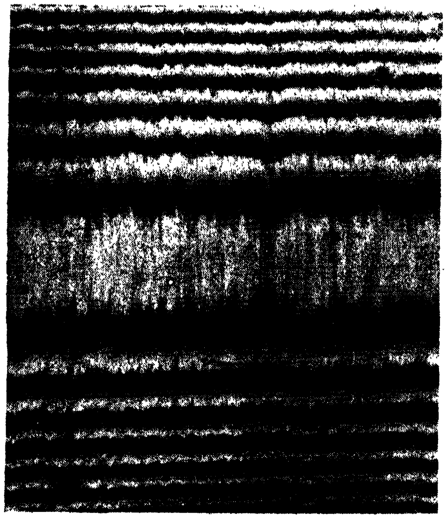


FIG. 52.—Finish of a rough lapped surface.

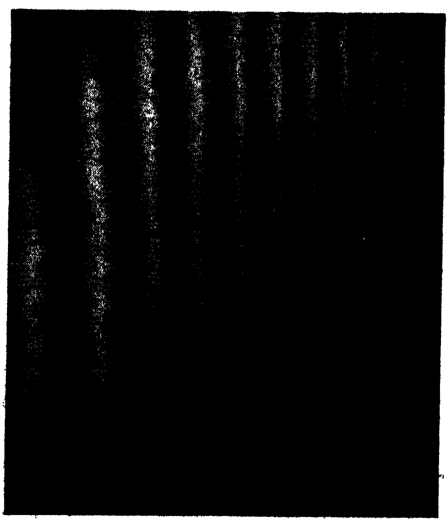


FIG. 53.—Finish of a lapped surface showing a scratch across right side ·00003 in. deep. Note the burr raised on either side of the scratch to a height of approx. ·000003 in.

A material has been produced. Metallurgically it belongs to a certain known standard. When machined it acquires a known dimensional standard, and in consequence it has a surface.

How is this surface to be specified?

Of all the problems connected with machining processes the evaluation of the surfaces is the least defined. If it is specified at all it is in such terms as "ground finish", "turned finish", or "lapped", and from the point of definition, such as a standard demands, this type of vague specification is in effect valueless.

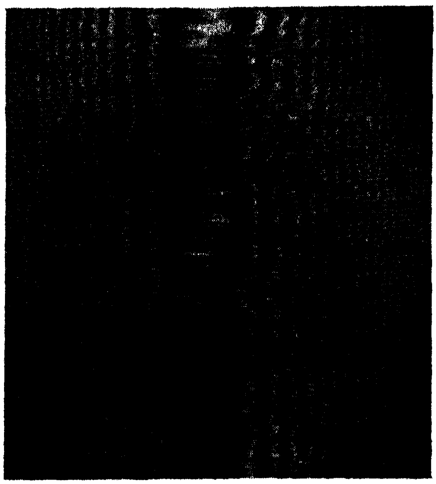


FIG. 54.—Fine ground surface.

The question is one which is receiving a lot of attention to enable an acceptable standard to be reached which may be put into concrete form, and suggestions by the British Standards Institute that surfaces should range in geometric progression from 1 to 200 allows for the fine surface finishes to be covered by the lower figures while the coarser finishes use the higher figures. It follows, therefore, that if a surface finish can be standardized so that reference to a chart or table is all that is required to obtain a properly understood specification of the finish, it will be of considerable value in the production of component parts.

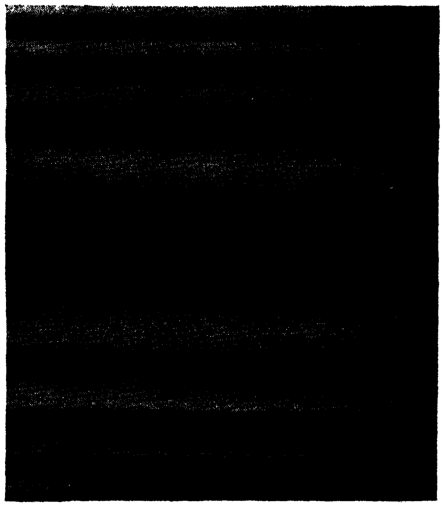


FIG. 55.—Finish of P.V.E. optical flat showing no measurable deviation from a truly smooth surface.

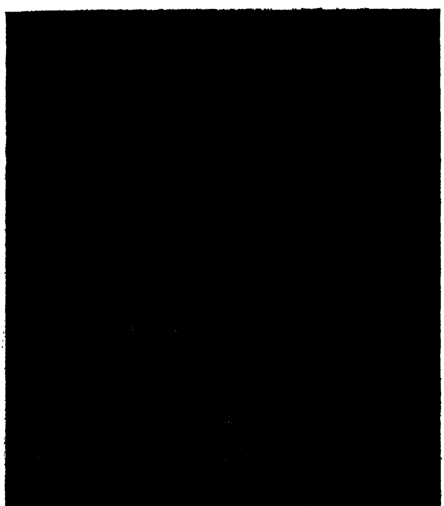


FIG. 56.—Diamond tool with smooth surface except for slight undulations and with speckled and grained background.

Surface Qualities.—The physical characteristics of a boundary which separates solid metal from other materials.

Surface Deviation.—The departure of the actual surface from the nominal surface. Also classified as surface flaws, roughness and waviness.

The American Standards Association scales are given as a guide to a general system, and these scales are operative with the American surface instrument previously mentioned.

SYMBOL	ROOT MEAN SQUARE *Inches*	HEIGHT OF IRREGULARITIES *Micro-inches*
63 M	·063	63,000
16 M	·016	16,000
4 M	·004	4,000
1 M	·001	1,000
250	·00025	250
63	·000063	63
32	·000032	32
16	·000016	16
8	·000008	8
6	·000006	6
4	·000004	4
2	·000002	2
·5	·0000005	½
·25	·00000025	¼

The fundamental difference between the American system of recording average meter readings and the British method is that American instruments are calibrated in root mean square (R.M.S.) of the height or depth of the irregularities, while the British instruments are expressed in the arithmetical height average.

In order to obtain a basis from which standards of the graphs could easily be compared in their true perspective it was decided to produce a graph of a good quality plate glass surface, with the result shown in FIG. 57 and this figure may be taken as a standard in comparing the subsequent graphs, all of which are the same magnification. A very fine surface graph or profile was obtained, being broken only where a very fine hairline crossed the glass.

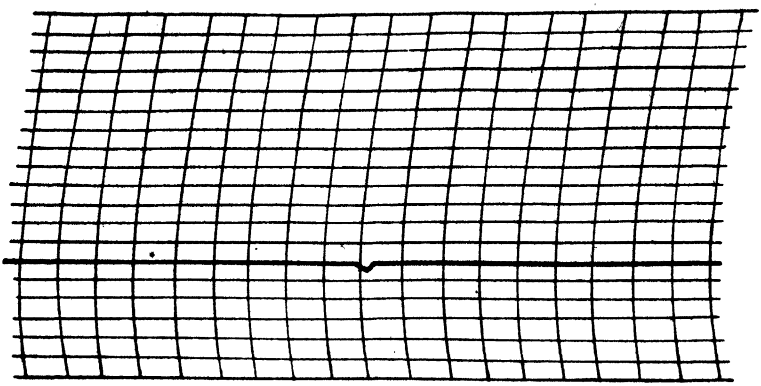


FIG. 57.—Graph of sheet glass; magnification V. 40,000, H. 200.

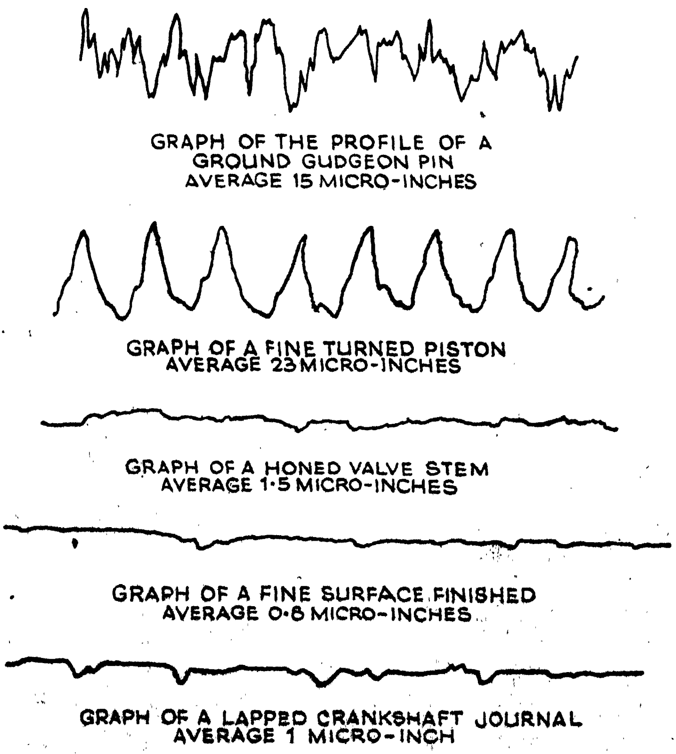


FIG. 58.—Comparison graphs of machining processes.

Taking the machining operations in the order as in SECTION 4 the graph on FIG. 58 shows the results obtained in measuring a motor vehicle piston which has been fine turned with a diamond pointed tool.

This establishes proof of the consideration of piston and cylinder brought out in SECTION 2, which shows a fine turned piston in a cylinder bore.

The high peaks of the surface, above the actual bearing metal, are shown clearly in FIG. 58.

The graph of the surface of a ground gudgeon pin is seen in FIG. 58, and a distinctly irregular surface is caused by the action of the multitude of minute cutting edges of the grinding wheel.

The honing of a valve stem gave the graph in FIG. 58 which indicates a marked improvement in the quality of the surface.

The lapping of a crankshaft journal produced the result shown in FIG. 58. This was a hand operation, a diamond dust lap being used which necessitated a considerable amount of time being expended.

FIG. 58 also shows the profile of a valve stem which has been superfinished, the fine surfacing being carried out after a grinding operation to produce the required dimensional accuracy.

The area of bearing surface is clearly seen in the later graphs, and such scratches or valleys as remain after being processed are below the actual bearing surface, thus affording pockets for the distribution of lubricant during the actual working of the surfaces. From a draughtsman's point of view the specification of a required surface is a very unsatisfactory procedure. Symbols are used which are variously termed "machine all over", "grinding", "machine finish", and so on, but a little consideration will show that such a specification is out of keeping with all the rest of the scientific methods used in demanding other standards during the production of components.

Two methods are in general use for computing the results of any surface profile in micro-inches. The American method, known as the "root mean square", represents a running average height of surface irregularities. Mathematically the average is taken by squaring the individual values, computing this average and then taking the square root.

The formula thus becomes:

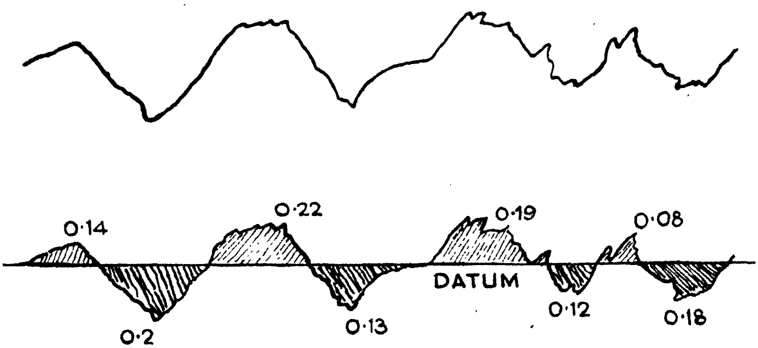
$$\text{Root Mean Square} = \text{R.M.S.} = \sqrt{\frac{A^2+B^2+C^2+D^2+\ldots}{N}}$$

Average Average

Where N = number of points taken.

The second and English method is the arithmetical height average, the formula of which is:

$$\text{Arithmetical Height} = \frac{\text{Areas above Datum line} + \text{Areas below Datum line}}{\text{Length of record} + \text{Vertical Magnification.}}$$



Vertical magnification 16,000.
Horizontal magnification 100.

Areas:

Above Datum	Below Datum
·14 sq. in.	·20
·22 ,,	·13
·19 ,,	·12
·08 ,,	·18
·63	.63

$$\text{Av. height} = \frac{\text{Areas above} + \text{Areas below.}}{\text{Length of record} + \text{V.M.}}$$

$$= \frac{\cdot 63 \times \cdot 63}{5 + 16{,}000} = .0000158 \text{ in.}$$

$$= 15\cdot 8 \text{ micro-in.}$$

FIG. 59.—Example of average height calculation.

The profile record produces a true profile curve and it is this curve which may be evaluated in order to obtain the true characteristics of the surface.

The mean height is denoted by the symbol $h\,m$ and naturally depends on the position of the base line adopted, which may be a line passing through the centre of the curve in order that areas above and below this line are equal, or it may be a line passing through the lowest points of the profile; and in this case $h\,m = \frac{1}{VL}\int_{O_B}^{L_B} y\,dx$ where the suffix B refers to the datum.

The average height is generally denoted by *h ave* and is shown in FIG. 59, where it will be seen that the areas above and below the datum line are within 5 per cent. of equal, which may be recorded as

$$h\,ave = \frac{1}{VL} \int \frac{L_C}{O_C} \sqrt{Y^2}\, dx$$ where V = Vertical magnification,

L = Length of pen record and the suffix C refers to the centre datum line.

The values obtained for either *h ave* or *h m* are very similar for practical work, that the employment of American instruments does not require the re-computing of obtained values.

Surface Macro

Apart from the type of surface roughness which is measured with the instruments previously described, consideration must be given to surface macro, and by considering FIG. 61 and

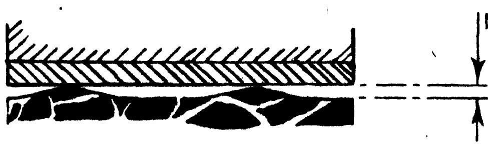


FIG. 60.—Sketch showing effect of macro surface on maximum bearing area (M).

comparing the two graphs it will be noticed that the surface undulations are of a different character. They tend to represent hills and valleys rather than sharp peaks and ravines. It will also be noticed that the traverse length of the graph is 2 in. rather than something in the nature of ·125 in.

FIG. 60 is, in effect, a profile recording of the macro surface of a grinding operation.

The macro surface is associated with a number of varying conditions of the machine tool traverse and also the vibration of the cutting tool. The pitch of the undulations will be seen to be far greater than the depth.

The importance of this surface condition cannot be overstressed, as it has a direct effect on the load-carrying capacity of two bearing surfaces.

The reasons for any serious waviness in a batch of component parts may be looked for in the machine tool concerned, and it is frequently found that the two main causes are conditions of the driving spindle and incorrect tool feed.

Recording instruments have been developed for measuring macro surface as distinct from those instruments previously described, and comprise of an exploring arm to which is attached

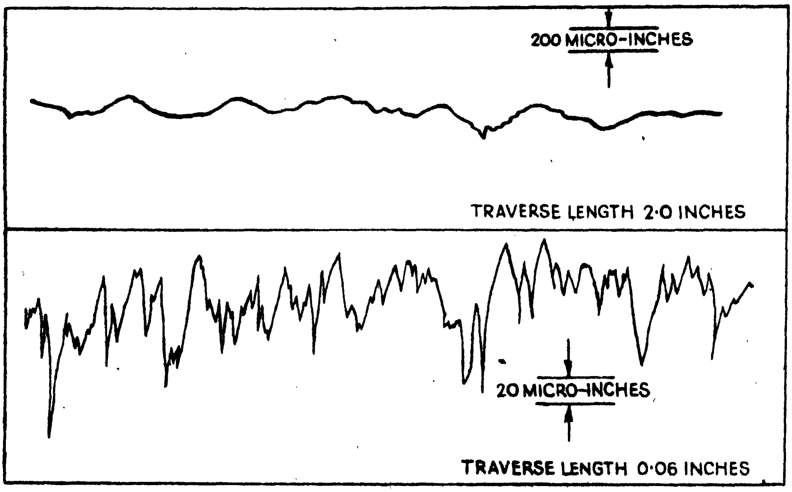


FIG. 61.—*Above.* Macro-profile graph.
Below. Micro-profile graph.

a suitable spherical foot which is large enough in area to travel over the micro surface yet small enough to record the waves and undulations which have a pitch of more than ·040 in.

Thus it will be seen that in order to assess any component surface accurately it is necessary that both micro and macro surfaces shall be considered in the light of the work for which the component is required.

SECTION EIGHT

Inspection Department Requirements

THE practical application of surface measurement is one of the jobs within the scope of any inspection department, being of equal importance with dimensional accuracy, especially since the two are closely allied.

The object of inspection is first to attain and then ensure the maintenance of specification.

Standards for dimensional and surface accuracy having been settled, it is the task of the department to ensure that such standards are maintained.

The surface standards depend entirely upon the use to which the surface is to be put, and the designer knows the standard required by experience.

One important factor of surface quality is the measurement of roundness or flatness, as the case may be, since it is quite possible to have a very smooth surface according to the surface recorder, but which is nevertheless very uneven.

For example, two surfaces working together may carry a load on several local high spots rather than over the maximum bearing area. This creates excessive pressures between the surfaces, and will ultimately lead to breakdown in one or both of the working surfaces. This is indicated in FIG. 60.

The major requirements for bearing surfaces may be grouped as follows:

(*a*) An even surface, free from waviness and chatter marks.

(*b*) A finish as fine as possible, having consideration of the method of lubrication being used.

(*c*) Freedom from defects created by overheating during the machining operations, or by embedded matter and abrasives.

The machined surface finish may be used for the inspection of previous operations, especially in parts which operate under considerable stress.

In the Magnaflux method, which is the method widely used for the final inspection of highly stressed parts, small defects are brought out so that any component which contains minute cracks in the metal may be scrapped before it has the opportunity to break down at what might prove to be a vital moment.

It has proved to be far easier to detect minute flaws in a surface, which may well develop into surface cracks, when the surface has a high degree of finish. The ability of a component to withstand stresses has been proved, both in the laboratory and under working conditions, to be largely affected by the finish of the surface, and it follows that in very highly stressed parts a surface defect does not need to be large in order to cause failure at the maximum load. The surface therefore of a component is a characteristic to be considered for itself, especially when it is realized that the breakdown of metal often starts with fatigue cracks at the surface which are fine enough to escape microscopic detection. Any assistance which can be given on the subject of inspection relative to the surface finish must therefore be considered, and in order to form a background to surface inspection. A few examples of the methods and instruments used in the light of modern inspection practice will now be considered, beginning with the introduction of gauge blocks for precision measurement by G. C. E. Johanson of Sweden in 1897. The surface of these gauge blocks is of such high quality that when two blocks are slid together they adhere in a way usually associated with magnetized metal.

Gauge blocks are produced with accurately formed parallel sides of definite thickness by processing blocks of steel through to the finish-grinding operation and lapping, thus ensuring accurate dimensional limits. Each block is then suitably marked by etching. The lapping operation results in a square dimensionally accurate block with two flat and parallel faces.

Probably the most common of gauges is the micrometer, which is in constant use in the inspection department.

Production gauges, generally known as gap gauges, are used only to indicate that a workpiece is within the required tolerance, because one end or gap goes over the component while the other end does not. Thus this type of gauge becomes a "go and no go" gauge. Adjustable gap gauges are available, such gauges being set to the desired tolerance by the use of accurate gauge blocks.

Many measuring instruments require the use of a surface plate, which is an accurately ground flat plate, ensuring the true relation of the instruments to the workpiece being inspected.

One of the latest materials to be used in the manufacture of these surface plates is glass, of about one inch thickness. Glass has properties which make it more suitable for this class of work than a cumbersome metal plate, in as much that it will not rust, corrode or burr, and is immune from changes in temperature and atmospheric conditions. Because of the comparative cheapness as well as availability of glass, gauges of this material are now being used to some extent. The advantage over metal gauges include their extreme hardness, which implies resistance to distortion. Their nature demands more care in use, and if dropped or otherwise damaged they are at once disposed of, which in turn eliminates many of the troubles arising when a metal gauge becomes slightly damaged although not sufficiently to become obvious to the user, even if the parts are obvious to the fitter when trying to mate them. It follows that the use of glass for gauges indicates that the surface finish for inspection gauges must be of the highest quality.

By combining many sources of data with practical experience, together with a résumé of methods developed by individual effort, the following information is presented, and should be studied in conjunction with SECTION 7 on measurement.

There are certain primary conditions which have to be controlled, and for which suitable measuring instruments are available.

Scratch defects. (*a*) Width; (*b*) Length; (*c*) Height; (*d*) Depth.

Location of scratch, above or below the datum line.

Direction of such scratches in relation to the working movement of the mating surfaces.

Percentage of load-carrying area to the total bearing area.

Waviness or chatter marks. (Width and height.)

The quality of the surface must be controlled throughout the manufacture of components, if the desired clearances are to be maintained, and attention to the quality of the surface finish allows very fine limits for the fitting of mated parts, such an example being that of cylinder bores which are commercially produced to ·0005 in. out of round, while pistons are fitted with ·0015 in. clearance. Crankshaft journals are held to limits of ·001 in.

Another branch of inspection related to surface finish is the checking for vibration of rotating parts, and modern balancing of such parts is carried out by the use of electronics; machines to register an unbalanced vibration of ·00003 in., as well as locate the position, have been used in aircraft production.

Turning now to some of the practical reasons for controlled surface finishes, these may be considered in three main groups.

Control of Component Dimensions

Interchangeability of working parts has become an essential part of modern machine production, and this demands accuracy of the dimensions of mating parts to fine limits. These fine limits on a surface such as indicated in FIGS. 60 and 62 cannot

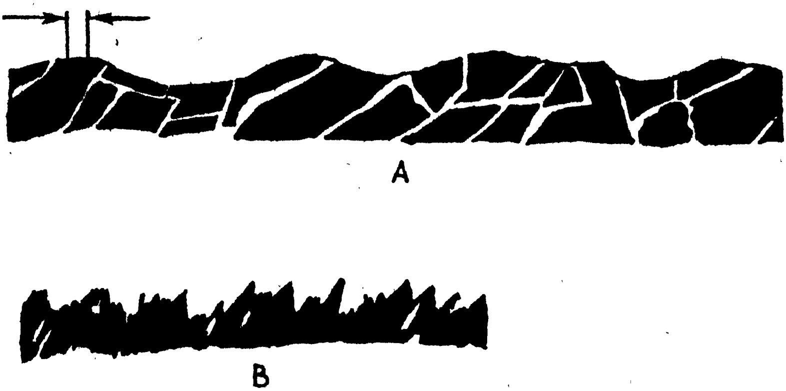


FIG. 62.—Sketch showing (A) macro surface profile and (B) micro surface profile. The difference in magnification is shown: The micro surface is the distance between the arrows on A.

be accurate if the surface is rough, because when the peaks above the maximum bearing area or datum line are removed, the clearance limit is increased.

This matter is further complicated by the fact that one or other of the mating components may be manufactured in some distant factory, but when the two parts are brought together they must be accurate.

Maximum Bearing Area

The practice of designing bearings with an ever-increasing bearing pressure while reducing the size of the bearing, has demanded that the fullest possible use be made of the whole bearing area.

It will be seen that the maximum bearing area is not available in the case of a surface, as indicated in FIG. 62, until such time as the peaks above the datum line are worn away, which is usually during a running-in period.

Increased Strength of Working Parts

The controlling of all surface irregularities which lower the fatigue strength of components, leading to ultimate failure, is emphasized when parts have to be light and yet maintain unusual strength in order to withstand high pressures.

A rough surface will result in high stresses at local points and surface scratches may develop into cracks. For example, in the cutting process the structure of the metal is disturbed for a distance below the surface which in turn may develop to surface cracks.

Magnaflux

The development of the magnaflux technique indicates whether or not magnetic discontinuities exist in the material at or near the surface of a metal component. Such discontinuities may be cracks or non-metallic inclusions, and defects at or near the surface are exposed by this process, which is based on the principle of magnetizing the parts to be inspected. The magnetism sets up a polarity between any cracks or separations, the parts being covered with an indicator in the form of finely-powdered black magnetic iron oxide, suspended in oil. These particles adhere to the surface of the workpiece wherever the polarity of a flaw or crack attracts them. Surface cracks as shallow as ·0002 in. in depth are revealed by this method.

In the case of highly polished surfaces where surface cracks may be temporarily closed by the polishing action, the inspector may not detect them by microscopic examination, but they will be revealed by the magnaflux method.

War production experience has shown that the measurement and control of surface roughness, waviness and chatter is a practical necessity in any programme of quality control, and research into the effect of surface roughness has been carried into the performance of parts. A quick and accurate means of checking production set-ups in order to determine the finish of parts coming from the machine has assisted inspection departments to inspect quickly and accurately a run of parts for the specified surface quality.

The recorded method of inspection utilizes one of the stylus-type instruments described in SECTION 7, and records obtained by this type of instrument on production work have to conform to certain pre-determined plus and minus limits, in order to pass inspection.

The tolerance on the roughness figure is required to allow variables which affect the surface finish, especially in a batch of components.

Analysis of a quantity of test pieces indicates that this tolerance may range between 60 and 240 micro-inches dependent upon the type of machining operation. During an analysis it is found that while the bulk of parts are to the specified standard, or even better, a small number of parts having a much higher or lower figure will demand a tolerance, and this makes it necessary to adjust the average figure to suit all the test pieces. The following figures in micro-inches indicate the variation of a batch of test components.

15 16 22 20 18 20 27 16 15 19 18 20 23 23 21 16 19 20 24 20 18 19 20 19 16.

The average figure for these twenty-five components is 19½ micro-inches, and the micro-inch variation is plus 7½ minus 4½.

Standard pieces are intended for use with a comparison microscope and must be made of the same material and receive the same treatment as the batch of components for which they have to serve as a standard.

The pieces should be measured at a number of points all over the surface in order that a reasonable average may be obtained.

FIG. 53 (SECTION 7) indicates the type of standard record which is in general use, and it will be noted that the profile is related to a datum line. All the calculations required should be detailed on a Standards sheet or card, and once the finish has been accepted as the one most suited for the specific application there will be no more reason to depart from it than there is for departing from standards of dimensional accuracy.

For parts already in manufacture, experience has shown that one method of establishing a basic standard of finish for that part is to measure a reasonable number of parts which have proved satisfactory both when fitting and in service.

For new parts the standard must be determined empirically by reference to known applications in similar characteristic.

Inspection departments which have adopted surface control have found that it is unnecessary to check frequently on the measuring instrument, if a visual checking method is introduced together with suitable reference piece.

Visual inspection is carried out with a microscope of low power magnification, by comparing the surfaces to be checked against a reference piece. A sample of the required standard is clamped in position on the microscope, and by inserting the surface to be inspected, the comparision may be made, since both the standard and the surface are clearly seen. Any degree of contrast of the two sections will at once be apparent to the inspector.

To maintain these pre-determined standards the inspector must be trained in this type of work, and correct lighting must be provided in order to prevent eyestrain. His knowledge must include a clear understanding of the types of surfaces produced by the various machining and finishing methods, and also the meaning of any variation from standard. It is largely dependent upon his knowledge that machines, on which the surface is produced, are checked for faults and so prove of advantage in the maintenance of the machine.

Serious deviation of the surface quality, using the same machine and procedure throughout the run, may indicate some mechanical trouble with the machine or the cutting tool, or improperly applied coolant.

Undue macro-surface may be caused through loose bearings in the headstock, or indicate that the tool setting is inaccurate.

Any tendency to chipping or burning indicates that the coolant or cutting fluid is not functioning correctly, or is wrongly applied.

Surface analysis will define the correct type of cutting tool to be used on the material, and by considering the type and quality of the material being worked, the speed and feed for cutting is determined.

A recent method of quantity inspection has introduced an instrument which uses a point of light to explore the surface of the component.

The components to be checked are passed under the light beam at a constant rate by a conveyor, and the inspector observes a dial, noting any variation which may demand the closer inspection of the particular part which caused the variation.

Practical experience has shown that the probable error when using visual methods of any sort should not exceed 15 per cent., and it is usual to use a reference piece with a roughness standard at least 10 per cent. higher than that of the lowest acceptable standard.

By collecting results obtained in those inspection departments which have instituted systems of surface control, no manufacturing complexities have been introduced. On the contrary the result has been to effect certain manufacturing economies. A number of instances have shown that by the introduction of surface control it has been possible to utilize less costly production methods, and the following is a list of advantages which rapidly prove the worth of this department:

(1) It ensures that the designer's requirements are carried out.

(2) Ensures guaranteed uniformity of surface whether of one batch of components at once, or a large number of batches over a period.

(3) Ensures that the degree of surface finish is to the standard most suitable for the work which the surface has to perform.

(4) Assists the dimensional control of parts and the maintenance of limits by taking such dimensions on the base metal rather than on a series of uncontrolled surface peaks.

(5) Ensures that dimension checks are not taken between or over waves or chatter marks on the surface.

(6) Assists production departments in the choice of a series of machining operations required.

(7) Components which are not manufactured on the premises are ensured the desired standard of surface finish because this can be correctly specified on the drawing and by the specification department.

(8) Economies are effected in the processing of parts.

(9) The uniformity and interchangeability of component parts is assured.

(10) Tool life may be increased by the control of the cutting surfaces.

(11) Machine tool faults may be observed and remedied before actual breakdown, by the observation of any progressive deterioration in the surface quality of a batch of parts.

(12) Correct type and use of coolant may be determined.

(13) Scrap will be reduced to a minimum, especially when large quantities of one part have to be manufactured.

(14) In the case of grinding processes, the surface variation indicates a number of common faults during the operation, as indicated in SECTION 5.

The equipment required by an inspection department for the handling of surfaces must include a comparison microscope or an electrical means of inspection if the quantity of parts demand speedy methods.

The situation of the surface recording instruments either in the inspection department or the laboratory must depend upon the layout and individual ideas of the factory management.

FIG. 63.—Composite surfaces.

The standards and the standard cards required by the inspection department must be filed within easy reach of each inspector.

In order to show the types of surfaces produced by various machining operations, a series of photomicrographs are reproduced in FIGS. 64 and 65, together with their respective values in micro-inches, and these should be closely studied and compared in order that the type of surface produced by any class of machine cutting tool may be easily discerned.

Inspecting Diamond Turned Components

The use of a surface recording instrument is required first to check the setting of a diamond tool, and then to take check readings after the production of a given number of components.

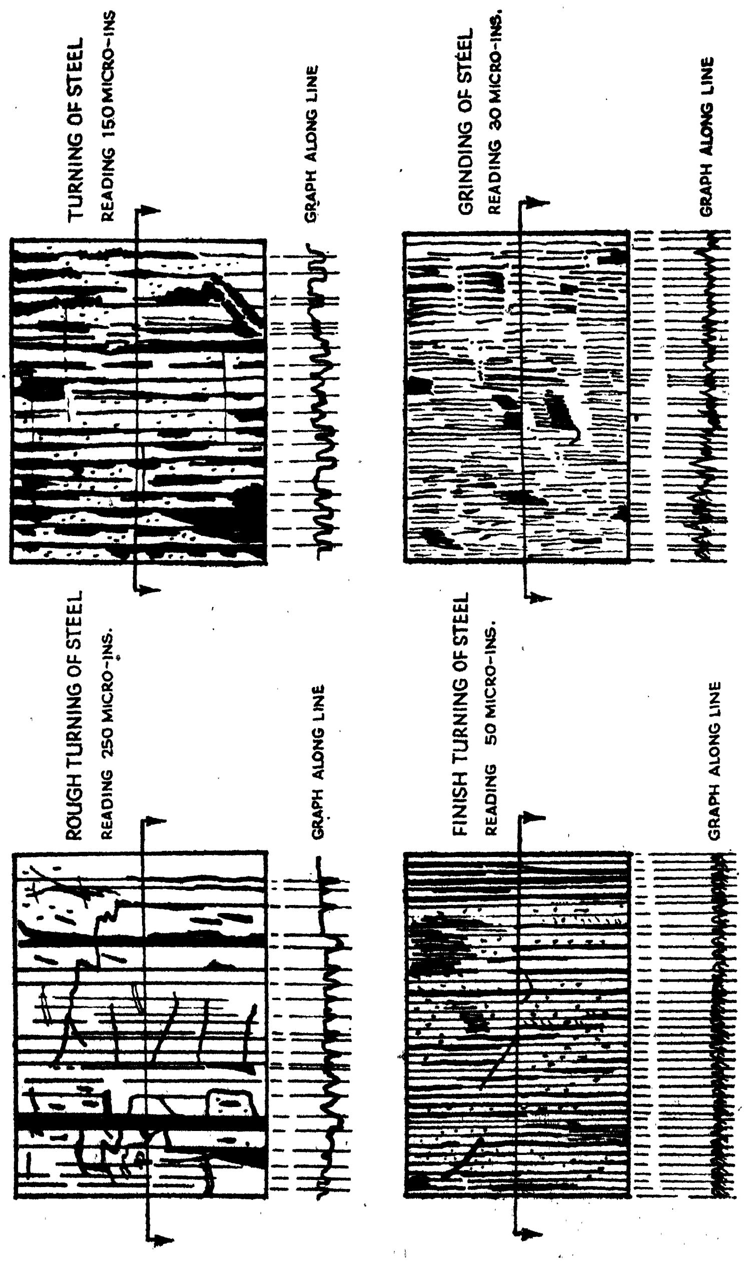
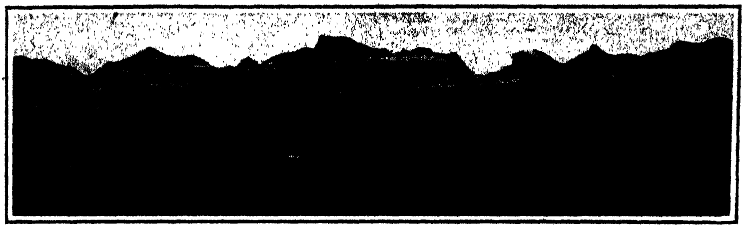
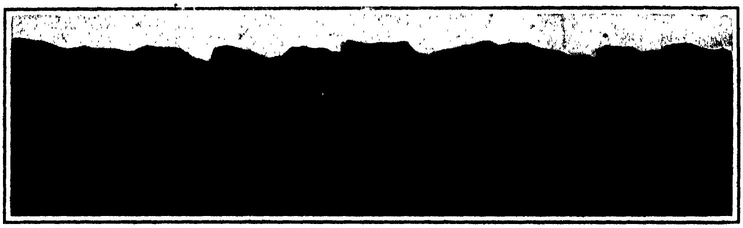


FIG. 64.—Sketch of types of surfaces with graphs.

Photographs 210 times magnification.

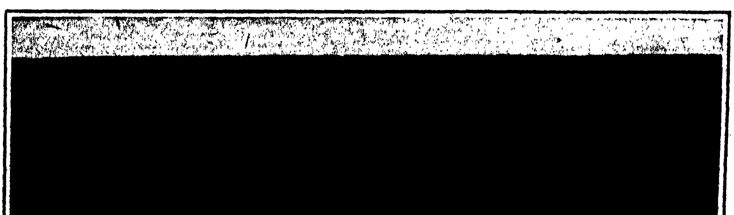


Wilmet Brand Cutting Tool rough ground.



Wilmet Brand Cutting Tool finish ground.

Wilmet Brand Cutting Tool lapped with Spedia Wheel.



Ordinary Razor Blade (for comparison purposes).

FIG. 65

The graph produced on this type of surface will remain consistent so long as the setting remains unchanged, and the tool cutting-edge is undamaged by hard inclusions in the workpiece material.

After any adjustment to the setting of the tool it is desirable to record the surface produced in order to ensure uniformity of the quality of surface finish.

SECTION NINE

Research

THE problem of research is primarily a matter of recording and analysing the great mass of data which is obtained by experiments, and these notes are, in general, results of research carried out during the period 1938-1944.

Ideas must be formed on the basis of some known theory, such ideas being worked upon, each process and result being carefully recorded and analysed. In this way has the present knowledge of chip formation and removal been obtained, as well as of the type of surface produced and the machine and cutting tool which produced it.

It is in this way that the scientist and research engineer build up a detailed knowledge of the properties of materials and processes in order that such materials and processes should be used to the greatest advantage.

The surface factor of component parts was recognized as being of considerable importance through the War years 1939-1945, and considerable research has been undertaken into the factors affecting the ultimate surface produced.

These factors are grouped into three main parts for practical consideration:

(1) Composition of metal and its physical properties.
(2) Heat treatment of metal.
(3) Machining and finishing of metal.

Taking these in order, the following examples and notes on research are of a certain practical nature and have assisted in the attainment of the high quality required for modern engineering.

1. Composition of Metal and its Physical Properties

This is discussed at some length in SECTION 3, although some notes on the use of X-rays will be of interest. The fact that, when working parts are designed, allowances over the maximum stress are permitted, indicates that careful examination of materials is required.

One of the most modern means of inspection is the X-ray. In the analysis of metal structure the X-ray is far superior to the microscope, largely because it enables the observation of the interior for inhomogeneities.

Briefly, X-rays are light rays of a very short wavelength which overlap the ranges of both gamma rays and ultra-violet rays.

In view of the short wavelengths, or greater frequency, X-rays penetrate deeply into metals, and observation may be made on molecules and atoms. The aim of X-ray examination is to determine the arrangement of atoms and molecules in the crystalline structure of metals, thus allowing the accurate determination of heat treatment analysis, the control of grain growth, the determination of internal stresses and deformation, and the accurate differentiation between the interim structure and the surface structure after machining.

Indeed X-ray industrial applications have become widespread, and probably the widest use is on castings, in order to determine such defects as blow-holes, slag and sand inclusion, porosity and cracks.

In the inspection of aircraft working part surfaces, which have to withstand high pressures, surface cracks have been determined which might otherwise have passed unnoticed.

2. Heat Treatment

This is dealt with in SECTION 3.

3. Machining and Finishing of Metal

The need for a clearer understanding of the complex factors and variables involved in the cutting of metals is emphasized by the increased demand for more precisely shaped and dimensionally accurate parts.

Progress has been rapid largely through the research and development of alloy steels and improved tool materials.

In any metallic cutting process an ended tool is guided through a pre-determined orbit with respect to the workpiece and removing excess metal in the form of chips.

The speed, accuracy and efficiency of this operation depends on a smooth and properly proportioned chip flow, which in turn is governed by the dimensions of the cut, the metallurgical characteristics, shape and velocity of the tool, the hardness, elastic and plastic properties of the metal being cut, and the lubricating and cooling properties of the cutting fluid used.

Much information has been gleaned from a study of the structure of a chip, especially with the use of high-speed cameras, and it has been found that chips are divided into three main groups: (1) fragmented, (2) segmented, and (3) plastic flow.

Fragmented chips are the result of the crushing and fracturing of brittle metal, and show little evidence of flow.

Segmented chips are developed by a combination of flow and rupture and usually result when ductile metals are machined, using heavy cuts. Flow chips are generally continuous, being produced under balanced conditions of speed and depth of cut, and show definite flow structure.

In general, chips curl smoothly away from the cutting edge of the tool, and are in regular spiral or helical form, with the convex surface nearest the tool edge comparatively smooth, while the concave side is very irregular and shows definite signs of deformation of the metal structure.

Further investigation into these facts suggests that chips are the result of severe plastic deformation.

The general advance towards the goal of efficient metal machining of all metal-cutting tools has been the natural outcome of research, and this has been assisted by the progress made in the field of surface finish generally, which allows scientific investigation to be carried into finish machining operations.

In this Section consideration is given to the cutting tool in the light of the very considerable investigations made to increase the cutting ability at higher speeds and feeds, with longer tool life, and at the same time ensuring a cleaner, finer finish to the component parts. It is interesting to note that in 1904 Dr. J. T. Nicholson of Manchester reported on the application of single point tool pressures which were necessary for turning work.

The vertical pressure is that which is exerted by the workpiece on the tool edge. Surface pressure is the pressure at right angles to the tool edge. Transverse pressure is caused by the tool being fed horizontally into the workpiece.

By his experiments into chip action during operations Dr. Nicholson determined the wave caused by the increase and decrease of pressure on the cutting edge of the tool during operation. He also determined the heat which is generated in bending the chip and was of the opinion that more heat was generated by molecular disturbances in the metal than through the actual pressure of the chip on the tool.

The following details are given in the light of the most modern cutting practice, and the tool data in general terms for the factors relating to the cutting edge is given in FIG. 66.

High-speed photography has shown that the action of the cutting edge upon the workpiece is, in effect, a process of deforming the metal structure to such an extent that it fails by the

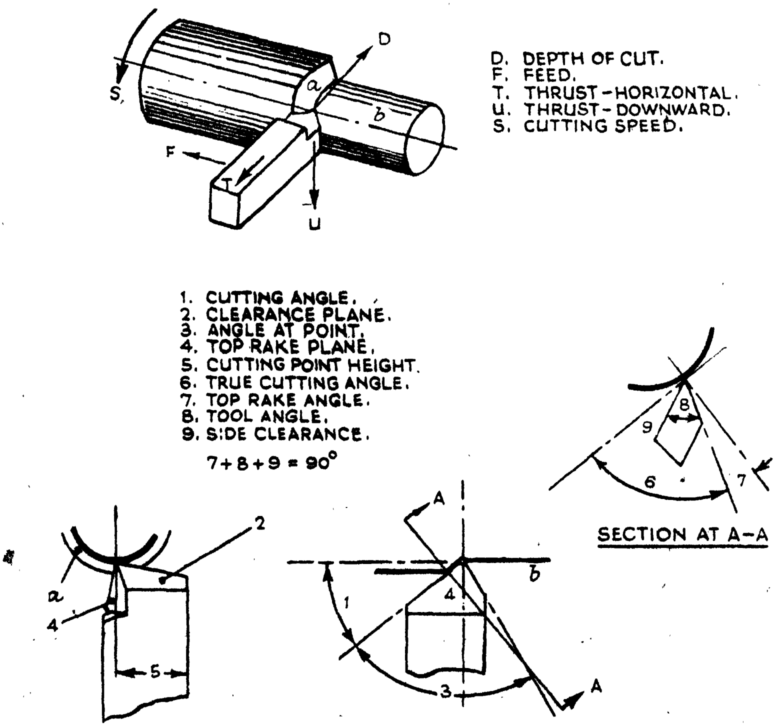


FIG. 66.—General cutting tool data.

forces of shear. The edge penetrates because the metal to be cut breaks down under the tremendously concentrated load at the cutting edge, and either by plastic flow or fragmentation allows the edge to advance. Progress continues until the load is distributed as the edge support structure comes into contact with the sides of the cut. If this interference is eliminated, the edge continues to advance and the cutting proceeds. In the machining process the chip performs this essential function of eliminating the material on the side of the cut. Basically the chip is not formed by the tool, but by the plastic or elastic forces developed in the metal of the workpiece as the result of pressure between the moving metal and the cutting edge. Such extrusion is not continuous but periodic according to the peculiar qualities of the grain structure. By observation of a chip under a microscope, a flow type chip is seen to consist of a succession of severely stretched sections or layers.

These layers are arranged radially with respect to the axis of chip curvature and may be flat or convexly curved upwards.

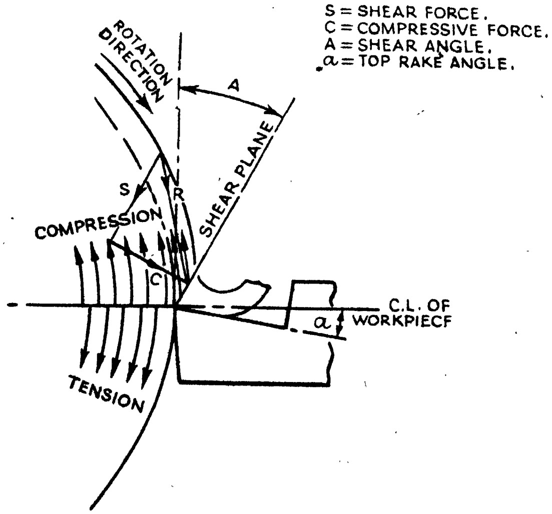


FIG. 67.—Sketch of stress distribution and force diagram relative to shear plane.

The line of demarcation between this deformed structure and the undisturbed metal is sharply drawn and extends from the tool edge in a perpendicular direction to the tool face to the point where the inside surface of the chip joins the workpiece (see FIG. 67). The direction of the chip layers intersects this line at an appreciable angle.

Apparently the flow or deformation which establishes the chip structure takes place in a comparatively small area adjacent to this line, and is the result of pressures exerted in a direction parallel to the chip motion. The area of plastic deformation is limited by the work-hardened metal of the chip, the advancing body of the workpiece and the orbit of the tool. The interplay of plastic and elastic forces result in a definite discontinuity in the chip motion, and the chip layers are formed by a series of alternate movements of compression and release of the plastic flow in the forming layer, followed by tensile separation at the tool edge, first towards and then away from the tool face. It follows that for this shearing and plastic flow to take place, forces are stressed in various planes in both the cutting tool and the material being cut.

At the point of shearing the force which is opposite that of the cutting point is radial compression, while the forces in

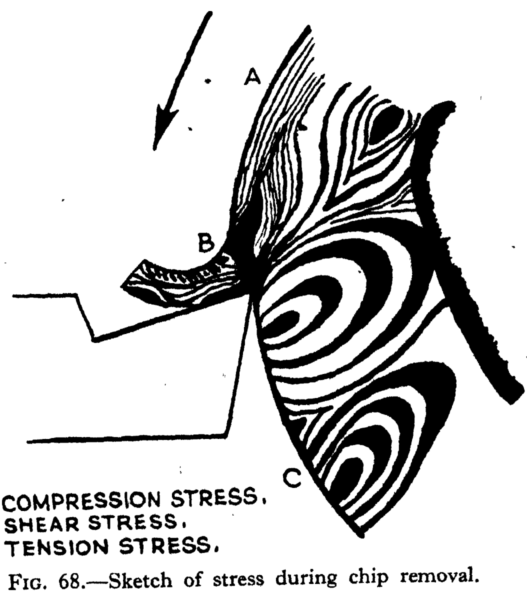


FIG. 68.—Sketch of stress during chip removal.

the metal which has passed the cutting point is that of radial tension. This is shown diagramatically in FIGS. 67 and 68.

Heat generated in both the tool and the workpiece is attributed to three major causes:

(1) Grain movements and flow which sets up internal friction and heat, such heat being absorbed by the workpiece, tool, chip, and coolant.

(2) The velocity of the chip coming from the main metal and sliding over the face of the tool.

(3) The coefficient of friction between the chip and the tool, which largely depends on the roughness of the tool cutting-edge.

It has already been stated that since the structure of the metal is in compression as it approaches the tool, and grain movement and flow takes place, it is possible for welding of minute particles to take place on the tool cutting-edge.

Following this theory the chip may be represented as splitting off from the workpiece and curling over the rake of the tool, with a crater forming at the point of the tool, and this crater may then be filled with the " built-up " edge, and thus supports the theory that the built up edge actually creates the cutting.

Turning now to the resulting surface of the workpiece after these forces have taken place, one result is a layer of permanently deformed material or fragmentation. This fragmentation will develop to smear metal when the cutting action causes plastic conditions of fragmentation, due to the generation of intense heat.

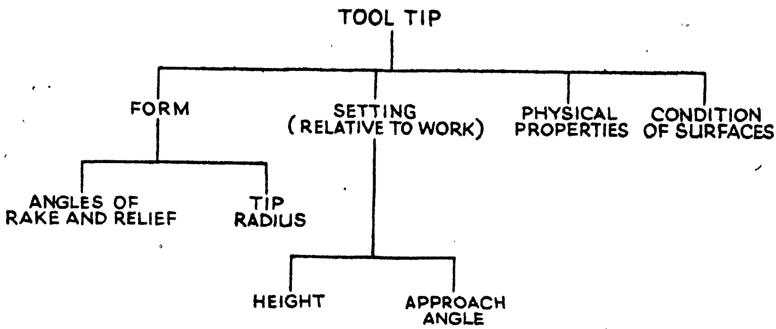


FIG. 69.—Chart of factors relating to a cutting tool tip which affect the life and performance of the tool.

By studying in detail the results of experiments in relation to the general tool data given in FIG. 66, and taking into account the heat generated as indicated above, it will be found that the ultimate surface is dependent in varying degrees upon the value of the co-efficient of friction. This co-efficient must have a bearing on the expressions of tools' rakes and angles, because it is upon these rakes and angles that the shearing action depends.

It has been stated earlier in this section that the efficiency of metal removal depends upon a smooth and properly proportioned chip flow, which is governed, among other factors, by the shape and velocity of the tool. Research into the relationship between the angles and rakes of cutting tools has produced certain practical results, regarding the type of surface produced. Reference to FIG. 69, the chart of factors which influence the performance of a cutting tool, will show that the form of the tool tip and the setting are of major importance. The physical properties include those which are required by the cutting tool, especially when it is red hot.

The condition of the tool tip surfaces, especially the top rake surface, must be studied if the chip, after shearing, is to slide easily away from the main metal with the minimum of friction between the chip and tool face.

While it may be stated that the value of a built-up edge provides certain protection for the cutting-edge when roughing cuts are taken, in as much as the cutting-edge is provided with a larger area to support the chip load, the reverse is true in any attempt to obtain a high quality surface. The built-up edge must be kept at a minimum, in order that the fragments when they break away do not mar the surface of the workpiece. One of the factors which assist in the reduction of built-up edge formation is the use of correct rakes and angles. Since these angles and rakes are of such importance, the main feature of their composition and construction will now be considered, together with the main forces acting on the tool.

Chip Shear Plane

This shear plane, which is shown in FIG. 67, may be taken for all practical purposes as a line from the point of the tool to a point on the metal, not at the moment of cutting actually effected by the removal, and is shown as *A*.

During the shearing action two major forces are at work in the main metal, a compressive force as the metal approaches the tool and a tension as the metal is released, the relation of such forces being largely determined by the height of the tool setting in relation to the centreline of the workpiece.

Forces Set-up in Chip

These comprise the shear force *S* and the compressive force *C* (FIG. 67). The force *S* is parallel to the shear plane and it follows that the result is obtained by the triangle of forces *S.C.R.*

To obtain the magnitude of the shear angle *A*. the equation is:

$$A = 45^\circ + \frac{a}{2} - \frac{R}{2}$$

where a = the tool top rake,

R = the angle of friction between the chip and tool face, and the coefficient of friction U may be derived from

$$U = \cot (2A - a)$$

By considering the triangle of forces in FIG. 67, the method of obtaining a practical cutting pressure is to use the equation:

$$\text{Cutting pressure} = 2Su \cot A$$

where Su is the ultimate shear stress of the material being cut.

The changes which occur in the metal during the process of shearing are as follows: the metal structure is compressed progressively as it approaches the cutting edge until the elastic limit is reached. The compressed metal then becomes sufficiently plastic to allow a certain flow until such a point is reached where a plane of shear is established and each portion of the structure passes through this plane of shear, forming chips which vary according to the type of material being machined.

Forces Acting on Tool Tip

It follows that the forces set up in a chip must have opposite forces in the counterpart—namely the tool cutting-edge or tip. There are two distinct groups of forces acting on a tool tip.

Group 1. Relating in general terms, as shown in FIG. 66, in which T = cutting force, R = radial cutting force, F = feed force.

Group 2. The forces of friction set up by the action of the chip sliding along the face of the tool.

Mechanics of Chip Removal

To indicate the importance which must be attached to the use of correct cutting and clearance angles the following represent results of a large quantity of tests, relating the angles of the cutting tool to the surface finish.

Surface Finish in Relation to the Cutting Speed

This factor of cutting speed is in general difficult to determine in order to produce any set rule, because of the other factors which affect it.

Nevertheless, by the use of carbide tipped tools upon material of a definite specification, it is possible to produce results to surface finishing which may be used as a basis for the testing of other materials. By following the chart FIG. 70, it will readily be seen that the speed most suitable for the particular metal to ensure a reasonable surface finish is 3,500 ft. per min. These graphs are constructed as the mean readings of eight identical tests.

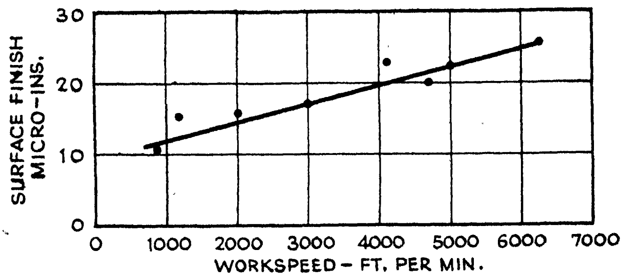


FIG. 70.—Graph of surface finish in relation to cutting speed using diamond-tipped tools.

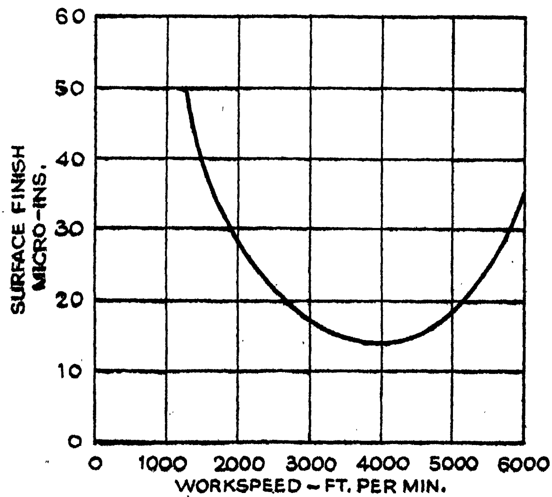


FIG. 71.—Surface finish in relation to cutting speed using carbide-tipped tools.

Surface Finish in Relation to Feed

The graph, FIG. 72, indicates that for fine finishing a fine feed is required, but at a certain point this rule no longer applies. It will be noticed that the effect of the feed is also proved on the profile graphs shown in FIG. 46 (surface graphs).

Surface Finish in Relation to Depth of Cut

In this case the graph, FIG. 73, indicates a steady and consistent tendency for the surface to become rougher as the depth of cut increases, and by reference again to FIG. 46 the profiles will be seen to be deeper. Now to relate the surface

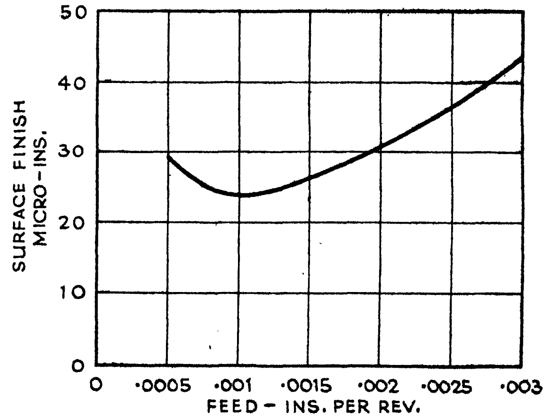


FIG. 72.—Graph showing relation of tool feed to surface finish using a diamond-tipped tool.

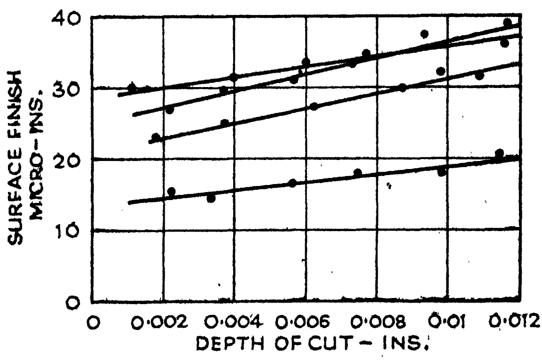


FIG. 73.—Surface finish in relation to depth of cut. Feed ·001 in.

finish to the characteristics of the tool angle and rakes. The following graphs indicate the correct angle for application and at the same time show the surface to be expected by using larger or smaller angles. By this means it is possible to obtain satisfactory results for all types of metals, although the process is naturally long and involved as it is necessary to make a number of tests, using the same material and the same tool which has identical characteristics, thus producing a number of results. The meaning of these results may thus be taken as a practical indication of the most satisfactory angles and rakes to be used.

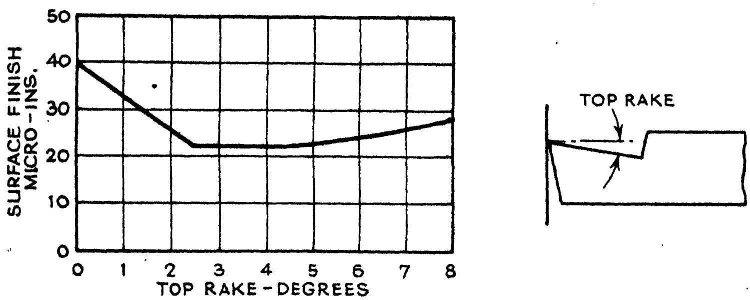


FIG. 74.—Graph of relation of tool top rake to surface finish.

Top Rake

This rake governs the flow of the chip from the workpiece and it is on this face that the friction between chip and tool may to a certain extent take place.

Resolving a number of tests on mild steel to a usable graph, shows that between 2 degrees and 5 degrees is considered suitable. The surface tends to become rather rougher after 5 degrees, although this may be in some measure due to a slight vibration set up in the tool due to the thinning of the section in creating the required top rake.

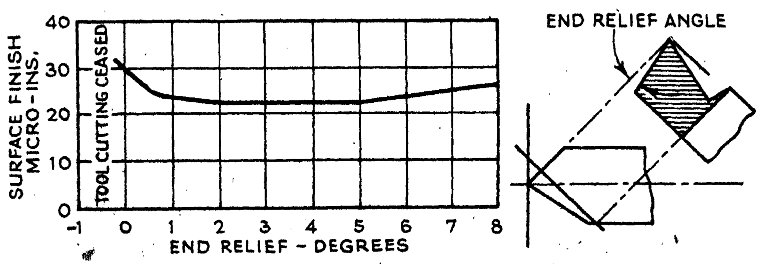


FIG. 75.—Graph of relation of tool end relief to surface finish.

End Relief

This appears from the graph (FIG. 75) to be fairly satisfactory set up to 6 degrees, but it should be noticed that from about ½ degree to zero, cutting action of the tool ceases and a burnishing effect is given to the surface of the workpiece.

Effect of Tool Height on Surface Finish

It will be seen in the graph (FIG. 76) that the effect of the height of the tool in relation to the axis of the workpiece is negligible until a critical point is reached.

This critical point bears a relationship to the end relief of the tool (FIG. 75) and it will be noticed in FIG. 76 that a burnishing action commences where the tool tip is raised above the axis of the workpiece to such an extent that cutting is not possible.

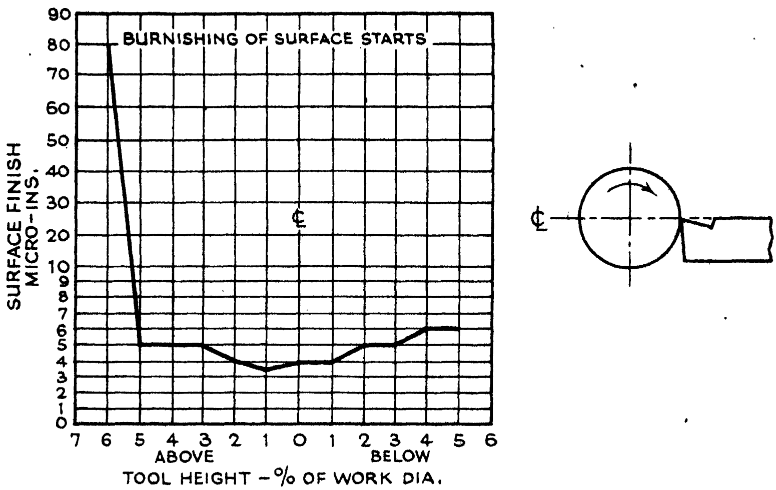


FIG. 76.—Graph of surface finish in relation to cutting edge height above and below workpiece centre line.

Cutting Tool Materials

From the beginning of the present century, scientific development within the steel industry has produced a new series of alloy steels whose properties are far in advance of those previously in existence.

Research into many materials suitable for cutting tools, especially for high speed production work, has resulted in tools being produced which give a long cutting life at high speeds, and this has a considerable bearing on the type of machine to be built for a particular operation.

Carbon steels have been processed, but by constant friction between the tool and the workpiece, the temperature of the tool may well go above the critical temperature of the tool steel with subsequent tool failure.

In 1868, Robert Muskett of Sheffield used air hardened high speed steel, and found that the maximum temperature of this type of tool was about 265 °C.

Early in the present century high speed steel was introduced, but as a tool steel it was not new in the chemical sense, but rather a considerable step forward in heat treatment of steel. The maximum working temperature for this type of steel was 550 °C.

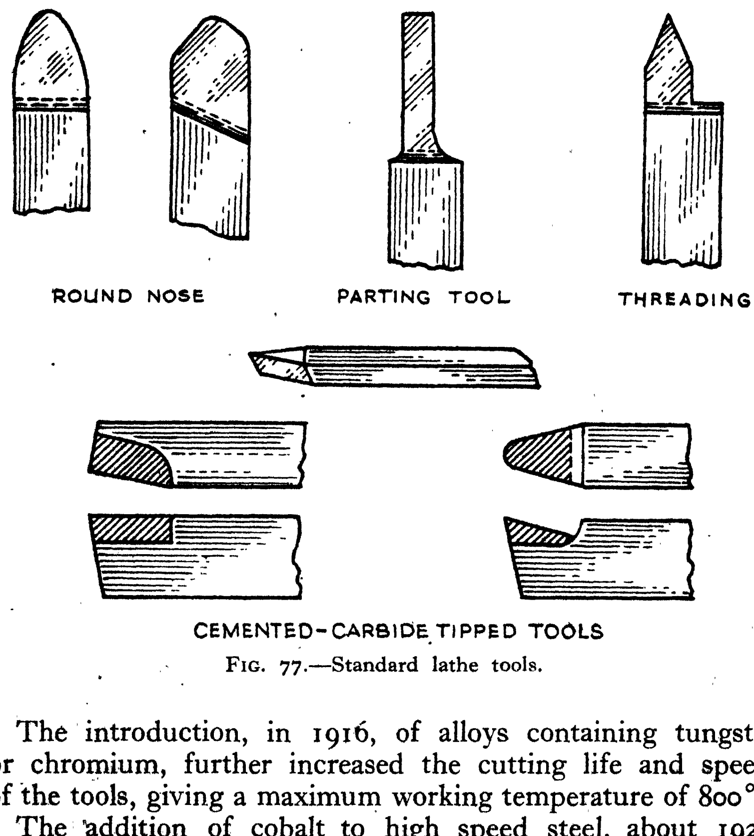


FIG. 77.—Standard lathe tools.

The introduction, in 1916, of alloys containing tungsten or chromium, further increased the cutting life and speeds of the tools, giving a maximum working temperature of 800 °C.

The addition of cobalt to high speed steel, about 1928, increased the actual hardness of the steel at the point when it was red hot.

In 1928 the cemented carbide range of tool tips was introduced and with these working temperature rose to 1,080 °C.

This type of tip was developed in Germany about 1928, and in 1929 began to assume a high position in metal cutting. Research in this type of tip had been going on from 1916.

Tungsten carbides are made from powdered tungsten, being formed into shapes, usually blocks, under pressure and then sintered at high temperatures. When processed these tips cannot be further heat-treated or forged in any way.

Apart from the high cost, it is not practical to make cutting tools completely of tungsten carbide, because of the extreme brittleness of this material, and so these blocks are brazed on to high carbon steel shanks by using a suitable brazing element.

Careful handling in the brazing of the tips to the shanks is required to prevent base-line cracks, which so often cause failure by fracture in many tipped tools.

Cemented carbide tips are brittle, having little or no elasticity, and cannot be subjected to any appreciable amount of vibration or chatter during the cutting process. This in turn has brought about the developments of heavier and more rigid machine tools, with a consequent increase in speeds and cutting powers, and a resulting increase in production with high quality.

The use of this type of tool required that the tool should be supported as far under the tip as possible.

It is essential that such tools are brought into the work at the full cutting speed, and the machine should never be stopped while the tool is engaged, since the decreasing speed sets up high stresses in the tool tip, and also the relief of torsion causes a backward movement of the work against the tip, thereby destroying it.

Milling Cutters

Milling cutters are divided into six main classes: (1) Roller Mills; (2) Side and face cutters; (3) Form cutters; (4) Form ground cutters; (5) Inserted tooth cutters; (6) Vertical milling cutters.

Each type follows the general principles of a series of teeth set in such a way as to produce a cutting action as the circular cutter revolves.

Some typical cutters are indicated in FIG. 26.

Research by the use of a high-speed camera on the milling cutter action has shown that each tooth, when cutting, puts an increased strain on the arbor to which it is fixed, thus causing the arbor to wind up. As the pressure on each tooth is relieved, the torsional energy in the arbor is released, causing the cutter to spring forward to the next tooth.

These intermittent cuts start at infinity and gradually pick up the shearing action in order to produce the chip. The series of operations of each tooth is a sliding action, followed by a crushing action as the tooth penetrates the workpiece. This is then followed by the shearing action.

This peculiar series of actions produces a hardening of the surface known as work-hardening, which has to be taken into consideration when designing milling cutters for use with certain materials (see FIG. 78).

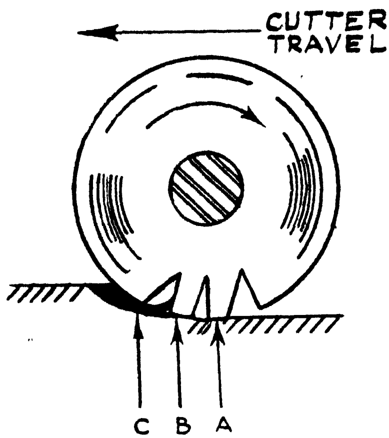


FIG. 78.—Action of chip removal during milling.

A. Sliding action. B. Crushing action. C. Shearing action.

Research has brought to the forefront a recent development applicable to milling cutters which are constructed with a negative rake.

Negative Rake Milling

The development of negative milling or hyper-milling since 1942, has offered great possibilities in the realm of increased production where milling operations are involved.

Speeds and feeds are employed in this method, which are fantastic when considered by standards of ordinary milling.

It has been a subject on which both individual and co-operative research has been carried out both in the U.S.A. and Britain. The technique is in effect the successful application, by scientific means of cemented carbides to the milling of steel. It has already been mentioned in SECTION 4 (Milling), that the operation is one of intermittent cuts, and during turning operations data was collected which enabled the present method to be developed. Reference has been made to the extreme brittleness of cemented carbides, and it will be seen that such tips can only be successfully used if the machine set-up is rigid, and the cutting speed sufficiently high.

One important requirement is that of giving a high degree of protection to the tip of the tool, and by considering FIG. 79 it will be seen that a negative rake gives a stronger cutting-edge than is possible with a positive rake, thus enabling it to withstand the severe shock which occurs during intermittent cutting.

During the development of the technique it has been proved that suitable conditions, especially in the milling machine,

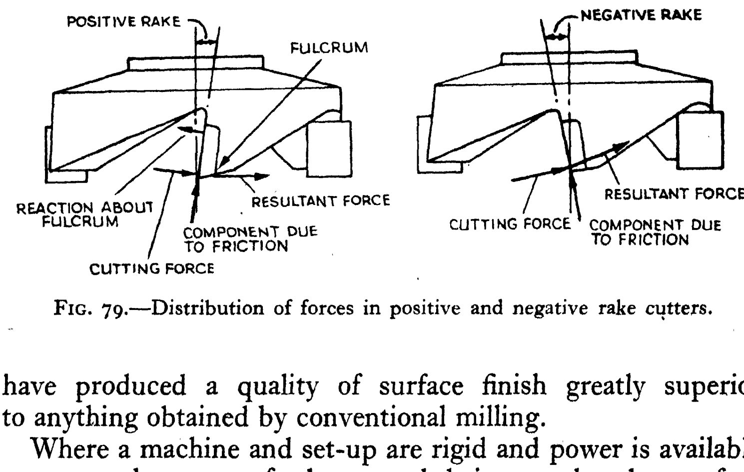


FIG. 79.—Distribution of forces in positive and negative rake cutters.

have produced a quality of surface finish greatly superior to anything obtained by conventional milling.

Where a machine and set-up are rigid and power is available to ensure the correct feed per tooth being employed, a surface finish of 20 micro-inches can be produced under production conditions. Such a surface would not require any further machining or finishing operation in many cases, and therefore it would be quite possible to eliminate grinding operations performed for the purpose of obtaining a high surface quality.

One theory advanced for such a resulting high quality of finish is based on the fact that a heavy rubbing action takes place between the work and cutting-edge similar to that indicated in FIG. 79.

This action is so severe that a high burnishing effect is created. The heat generated during chips removal is high, but such heat is found in the chips, and it is carried away by them rather than absorbed into the body of the workpiece; in fact the degree of heat in the body of the workpiece is less than with conventional milling.

The following notes are reproduced from "Negative Rake Milling" by permission of the Controller, Machine Tool Control.

Why Negative Rake is Used

The relative advantages of cemented carbides with regard to intrinsic hardness, ability to retain hardness at high temperatures and consequent abrasion resistance, have long been apparent and it has been mainly due to the difficulty of using such tips in milling cutters without cracking and chipping

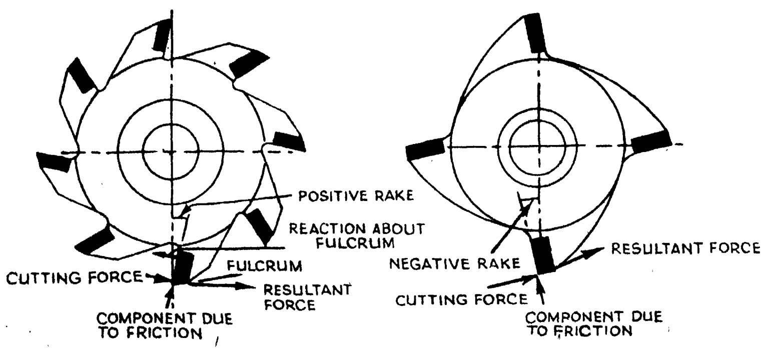


FIG. 80.—Distribution of forces in positive and negative rake cutters.

under the interrupted cut, that has retarded their application to rotary cutters. This weakness arose from the low tensile strength of the cemented carbide tips, a limitation which has led to the design of milling cutters in which the tip is mainly under compression during the cut.

Referring to the diagram of a conventional milling cutter in FIG. 79 it will be seen that the forces acting on the tip are such that they tend to pull it from its seating, and the cutting stresses must, therefore, be taken by the brazed joint in tension. A further point to note is that such a tip must necessarily have an included angle at its cutting edge of less than 90°.

The tips of a negative rake milling cutter (FIG. 79), however, are in compression and the cutting forces tend to hold the tip more firmly in its seating. Furthermore, the included angle at the cutting edge is greater than 90°, which results in a better distribution of stress and gives a stronger tip. FIG. 80 shows the distribution of forces in slotting cutters of conventional and negative rake types.

As the tip of a negative rake cutter is under compression during the cut, and the stresses on a positive rake tip are partly tensile (due to the bending action at the tip), it will be appreciated that the tip of the carbide-tipped negative rake cutter, being stronger in compression than tension, will be better able to withstand the cutting load, and less liable to fracture. A further advantage of the negative rake cutter is that the initial point of impact of the tip with the work is at a greater distance from the cutting edge than with the normal positive rake cutter, and the edge is, therefore, protected. This also helps in obtaining a gradual " build-up " of load, rather than a sudden shock as the tip enters the work.

Points to note before commencing application of Negative Rake Cutters to existing Production Jobs on Ferrous Materials.

There are two fundamental points which must be borne in mind throughout the application of carbides to milling practice.

The first is vibration, which must be avoided at all costs, as vibration or chatter of any sort breaks the carbide tips of the cutter. The second point to bear in mind is that of rubbing. Insufficient feed per tooth, feeding the cutter back over the surface that has just been milled, stopping the table feed whilst the cutter is still in contact with the work, must all be avoided in this connection. Rubbing causes the tip to overheat and so disintegrates its edges.

In order to overcome vibration the following points need careful attention:

1. A rigid machine tool is required.
2. Cutter bodies should be heavy to give a " fly-wheel " action.
3. The addition of a fly-wheel to the arbor as near the cutter

as possible reduces torsional oscillation, which is the primary cause of chatter.

4. Jigs and fixtures should be robust.

5. Workpieces that are inclined to "sing" should be given special care and attention to determine the best points to support them to avoid chatter.

To avoid rubbing, the points to note are as follows:

(1) Feed per tooth must be above ·003 in. per tooth and ·004 in.— ·010 in. per tooth is recommended. Although lower feeds are sometimes used, as shown in the examples, increased wear results.

(2) Ample power should be available to drive the cutter, as stalling in the cut not only gives rise to excessive rubbing but imposes great load on the tips and tends to crack or chip them.

(3) At the end of the cutting cycle the table should be lowered away from the cutter to avoid any rubbing action.

Operating Conditions

Before laying out an operation for negative rake milling, it is advisable to consider feeds, speeds, depth of cut and horse-power required.

When using high speed steel tools certain liberties can be taken with regard to the number of teeth in the cutter, tooth loading, peripheral speeds, and so on, but with tungsten carbide milling cutters more consideration must be given to their selection and application. The figures given in the table on page 148 and the examples of calculations involved in determining the number of teeth required in the cutter, the permissible depth of cut, and the horse-power required, will be helpful in this connection.

With negative rake carbide-tipped milling cutters, it has been found that a fairly accurate estimate of the horse-power required to remove a given volume of material can be obtained by working from the values in cubic inches per h.p. per minute given in the table on page 148. These figures are based on the normal capacity of negative rake cutters determined by experience on production runs.

The table also gives cutting speeds that have been used on various materials. These are by no means the highest at which carbide-tipped negative rake cutters can be used, but they represent what, to date, have been found to be economical speeds for general purpose work. For light cuts and finer finishes the peripheral speeds could be considerably increased, and for really heavy cuts it might be an advantage slightly to decrease the speed, but broadly, the speeds given in the table represent good average conditions in the light of tests undertaken by the Machine Tool Control and various manufacturers.

The feed per tooth is the distance advanced by the machine table during one revolution of the cutter, divided by the number of teeth in the cutter. This should not be less than 0·004 in. and can be increased to 0·010 in. when sufficient power and table feed are available.

The diameter and type of cutter used will naturally depend upon the particular job in hand.

Determining Number of Teeth in Cutter

A problem that frequently arises is the milling of a face of given width to a given depth in the shortest possible time using a particular machine, for which it is necessary to determine the number of teeth required in the cutter.

Assume for example a facing cut 4 in. wide and $\frac{1}{8}$ in. deep, on a block of mild steel of about 30 tons tensile strength, for which a vertical milling machine fitted with a 10 h.p. motor has to be used. Making an allowance for power absorbed in driving the table, gearbox losses, etc., and assuming that it is a good modern milling machine, approximately 8 h.p. will probably be available at the spindle.

Table Feed

From the table given on page 148 we find that we can remove $\frac{3}{4}$ cu. in. per h.p. per minute from this particular steel, or 6 cu. in. per minute in this instance (8 h.p. x $\frac{3}{4}$). With an area of cut 4 in. × $\frac{1}{8}$ in. i.e. $\frac{1}{2}$ sq. in., this means that a table feed of 12 in. per minute is possible.

Spindle Speed

For machining a 4 in. wide face, a 6 in. cutter would be quite satisfactory, and for a peripheral speed of 850 ft. per minute (obtained from the table) we find that the cutter should run at 541 r.p.m. or in round figures, 540 r.p.m.

Number of Teeth

For a minimum tooth loading of 0·004 in. feed per tooth, the number of teeth can be obtained as follows:

Revs. per minute × number of teeth × ·004 = table feed. (The table feed is in inches per minute.)

$$540 \times \text{number of teeth} \times \cdot 004 = 12.$$

$$\text{or number of teeth} = \frac{12}{540 \times \cdot 040} = 5\cdot 55.$$

i.e., 5 teeth.

Determining the Depth of Cut

As an example of a different problem, assume that we already have a cutter and a milling machine available and a particular job to be done and have to determine how deep a cut can be taken with safety.

Suppose the cutter is 8 in. diameter, and has 10 teeth. The job is in 50 ton tensile steel, the width of face to be milled is 6 in. and the machine has 12 h.p. available at the cutter spindle.

This is how the problem is worked out in detail.

From the table:

Peripheral speed = 600 ft. per minute.
Metal removed = $\frac{7}{8}$ cu. in./h.p./minute.

Spindle Speed

$$\text{r.p.m.} = \frac{(00 \times 12}{8 \times \pi} = 286. \text{ Say, 290 r.p.m.}$$

Table Feed

290 × 10 × ·004 = 11·6 in./minute.

Depth of Cut

(a) Volume of metal removed per minute = 12 h.p. × $\frac{7}{8}$ cu. in./h.p. minute = 10·5 cu. in.

(b) Volume of metal removed per minute = feed × width of cut × depth of cut. = (11·6 × depth of cut) cu. in.

Therefore, 11·6 × 6 × depth of cut = 10·5 and

$$\text{depth of cut } \frac{10\cdot 5}{11\cdot 6 \times 6} = 15 \cdot\text{in.}$$

Result of Calculations

Spindle speed, 290 r.p.m.; feed, 10·6 in per minute; and cut, ·15 in deep.

H.P. Required to do a Given Job with a Given Cutter

Another form in which the problem may be presented to the production engineer is that in which a certain job must be machined with a given cutter and the machine to do the job must be selected.

Assume that it is required to machine a component in grey cast iron and a cut 6 in. wide × $\frac{1}{8}$ in. deep is to be taken, using a cutter 9 in. diameter with 12 teeth.

The peripheral speed and feed are taken from the table and the running conditions are set out below:

From the Table:

Peripheral speed = 600 ft. per minute.
Metal removal = $\frac{7}{8}$ cu. in./h.p./minute.

Spindle Speed

$$\text{r.p.m.} = \frac{600 \times 12}{9 \times \pi} = 254. \quad \text{Say } 250.$$

Table Feed

$$\cdot 250 \times 12 \times \cdot 004 = 12 \text{ in./minute.}$$

Horse-power

$$\text{Metal removal} = 12 \times 6 \times \tfrac{1}{8} = 9\cdot 0 \text{ cu. in./minute.}$$

$$\therefore \text{Horse-power} = \frac{9\cdot 0}{\frac{7}{8}} = 10\cdot 3. \quad \text{Say } 11 \text{ hp.}$$

Machine Required

To be capable of:

Spindle speed 250 r.p.m.; table speed of 12 in. per minute; and horse-power at the spindle about 12 h.p. (allowing for some blunting of cutter).

By using the very simple and short calculations outlined above it is possible to arrive at practicable cutting conditions without resorting to dubious hit-and-miss trials which can have disastrous results. This is particularly important when using carbide-tipped tools, for stalling under load will inevitably cause chipping and cracking of the cutter tips.

A short calculation before commencing operations may also save disappointment caused by the purchase of a cutter which is too large or which has too many teeth to suit the capacity of the milling machine in question.

When milling at the high peripheral speeds permissible with tungsten carbide cutters, it is possible to instal larger motors than originally fitted to the machine. This does not impose a greater strain on the machine provided that the larger motor is not used at low spindle speeds. It has been found that with reputable makes of milling machines, a motor of ·50 per cent. greater power than the maker's original specification can be fitted for high-speed milling without harmful results.

Material	Tensile Strength tons/sq. in.	Recommended Cutting Speed ft./min.	Metal Removal cu./in./h.p. min.
Mild Steel	30	850	$\frac{3}{4}$
Mild Steel	35	800	$\frac{3}{4}$
Carbon Steel	40	750	$\frac{7}{8}$
High Tensile	45	700	$\frac{7}{8}$
,,	50	600	$\frac{7}{8}$
,,	60	500	$\frac{7}{8}$
,,	70	450	$\frac{7}{8}$
Cast Iron Grey	15 to 20	600	$\frac{7}{8}$
Inoculated (Meehanite)	20 to 30	600	1

Modern Methods of Sharpening Cutting Tools

To ensure that cutting tools give the most efficient life it is desirable to set a definite number of work-hours for each tool. This enables tools to be changed before the edge becomes completely dulled, and will also ensure that the minimum of material is removed during the grinding and sharpening process. It will also go a long way to ensure the uniformity of the surface finish being maintained.

The grinding method of sharpening is of such a speed and pressure as to create high temperatures in the tool. Such temperatures cause expansion in the outer surface of the metal. while the inner metal remains cool.

Grinding of Tools

Faults which are produced during the grinding of tools are similar to those described in SECTION 5, Grinding, namely, grinding cracks, chatter marks and scratches, burn spots and reduction of the cutting edge hardness.

It is not generally recognized that during correct grinding the tips only must be heated to high temperatures, but during incorrect grinding the part of the edge actually touching the abrasive wheel is heated to abnormally high temperatures, and stresses are set up in the structure of the metal, causing cracks to develop, especially during wet grinding, where the heated particles are quenched by the coolant.

Frequent causes of grinding cracks include the use of too hard a grinding wheel with too much pressure; grinding

FIG. 81.—Grinding cracks.

wheel out of balance, thereby producing local heat; or using a grinding wheel which is clogged with particles and so producing a burnishing action rather than a cutting action. The coolant may not be sufficient in quantity, or its application may be intermittent.

Cracks show up in the form of a fine network, as shown in FIG. 81, although it is sometimes difficult with the larger grinding cracks to distinguish them from cracks caused during heat treatment.

Grinding cracks usually lie at right-angles to the marks left by the grinding wheel, and are often concentrated at the edges of the tool.

Heat treatment cracks usually appear at the corners of the tool, by reason of the change in size of the cross section of the tool during treatment.

Alloy steel which has a low thermal conductivity is subject to grinding cracks because of the quantity of local heat developed during contact with the grinding wheel on the surface being slowly conducted to the interior of the metal.

In general, the higher the hardness of the tool the more liable are grinding cracks to develop.

As the toughness of steel is increased by correct tempering after the hardening process in order to relieve hardening stresses, tempered tools are less likely to produce a crop of grinding cracks, and grinding should always be undertaken after the tool has been correctly tempered.

In the grinding of cemented-carbide tools, different grinding wheels are used for the shank to those used for the tip.

A silicon carbide wheel is used for the tip, as a normal wheel makes very little impression.

The wheel must be sharp and clean, because a clogged wheel will generate excessive heat in the tip, producing dark patches and causing cracks.

The tool tip should be applied to the grinding wheel with a firm, light pressure.

The abrasive wheel should always revolve toward the cutting-edge thus ensuring that the tip is pressed firmly to its support in the shank, thus reducing the possibility of chipping.

To ensure a smooth, high quality surface the edge should be lapped or processed in some similar way.

Cutting Fluids

Attention will now be given to the question of cutting fluids, which is all too often taken lightly.

Recent progress in the science of metal cutting has included considerable research into the fields of cutting and grinding fluids, and all results of experiments state whether the operation was carried out dry or wet, and if wet, the details of the fluid are given.

Considering the action of a grinding wheel it will be seen to consist of a multitude of single point tools, and the function of grinding fluids is similar to that of cutting fluids. Due, however, to the high cutting velocity and the localization of high temperatures, the balancing of lubricating and temperature controlling functions call for a somewhat different treatment. Varying types of grinding fluids affect the operation so as to make the wheel act " harder " or "softer ", and thus another variable is introduced into the grinding process which, correlated with the wheel characteristics, may be used to advantage in controlling the results.

"Hard" oils are best used on soft, stringy materials, where the grinding speeds are lower, or where the maintenance of wheel form is important, for example in thread grinding, form grinding and internal work.

"Soft" oils are used when the workpiece is hard and when the surface is prevalent to discoloration or burning.

To emphasise the need for the careful selection of a coolant or cutting fluid the following examples are quoted, and all are taken from the production of war equipment.

For drilling connecting rod bearings in aircraft engines a change to a more suitable cutting fluid gave considerably increased cutting-edge life to the tools and produced an exceptional surface finish.

A firm engaged in aircraft work obtained the services of a specialist who overhauled the metal cutting processes, and by the scientific application of suitable cutting and grinding oils the operations were performed cooler, while the increase in tool life and the quality of the surface finish were very noticeable.

A job of drilling, reaming and tapping the rocker arms for engines necessitated the changing of the cutting tools four times each day. By the correct application of cutting fluids the tools required changing at the end of each eight-hour shift.

During the manufacture of gun parts the cutting tools required changing three times per normal shift. Again, by the scientific application of cutting fluids this change was reduced to twice during a normal shift, at the same time greatly improving the surface finish.

One more example: the drilling of aircraft parts having a Brinell hardness of 345. The drills averaged 29 parts before changing.

By using a suitable cutting oil these drills increased to 72 parts before requiring changing.

Increased production, longer tool life and better surface finish to parts of guns, tanks, aircraft, destroyers, hydraulic equipment, and so on, have often been the result of precision cooling in the place of haphazard methods.

From the above it will be seen that the cooling of the most highly stressed piece of metal, the tool cutting-edge, is in itself a scientific study.

Application of the fluid is equally important.

Consider a part which has been hardened, and on being ground for finish reaches a surface temperature of 1,090°C. and then the coolant is applied in a haphazard manner. The resulting condition of the metal surface is readily apparent to the eye, being a mass of surface cracks over the area which has been ground.

The condition is not so obvious if the part is of soft steel, since the result of such treatment is to put a layer of smear metal, caused by the surface layers becoming placticized, over the surface.

In general the most efficient results in machining are obtained when the cutting fluid is directed on both the tool and the workpiece, with sufficient volume to ensure flooding but without splashing.

It is essential that the fluid be kept clean and free from contamination, and also that chips do not interfere with the flow of the fluid, and for this purpose, filters must be included in every cooling system.

Turning now to the two broad chemical groups of cutting fluids—the first, cutting oils, and the second, emulsifiable or soluble oils—the cutting oils are classified as lard oils, sulphurized oils and chlorinated oils.

The development of sulphurized oils was a considerable forward step in the manufacture of cutting fluids. Sulphur, and many of its componds affect the metal surfaces and prevent bonding and welding. This is desirable to cutting surfaces as it reduces the tendency of chips to weld to the tool edge.

Emulsions may be considered in three phases, comprising the inner phase which consists of oil, the middle phase consisting of protective soaps and the outer phase, soap in water solution.

The outer phase governs the physical behaviour of the emulsion, while the inner phase is released to provide a measure of lubrication.

The advantages of cutting oils over emulsions for certain types of work, and *vice versa*, is rather a long subject for this book, but it will be apparent that the effects of cutting fluids will be seen on the cutting tool, the chip, the true dimensions of the component, and the quality of surface produced.

The principal functions of a coolant or cutting fluid may therefore be summarized as follows: (*a*) to carry off heat developed in separating the chip from the work, and thereby preventing a dangerous rise in temperature through the accumulation of such heat, (*b*) to lubricate the chip so that it will slide over the tool easily, thus reducing the generation of frictional heat, (*c*) to improve the quality of the surface finish, (*d*) to guard against rusting, (*e*) increase the life of the tool, (*f*) to flush out the cutting area and wash away the small chips.

The following information is reproduced with the permission of Messrs. Fletcher, Miller and Co. Ltd., from their booklet *Cutting Oils in Modern Production.*

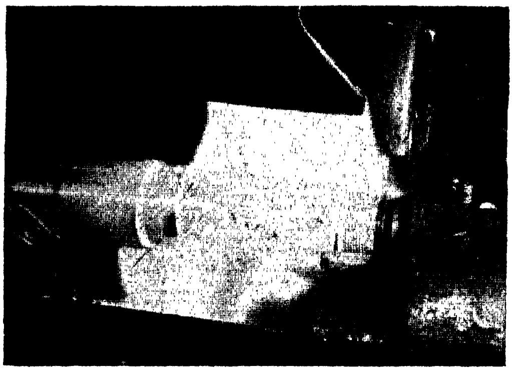


FIG. 82.—Grinding ball race fits on commercial vehicle wheel axle of 1 per cent. nickel chrome steel on Norton external grinder, peripheral speed 5,600 ft. per minute, using soluble oil at 1–45 dilution.
(*By courtesy of Messrs. Fletcher Miller Ltd.*)

In recent years cutting oils have become widely used in most machining operations, and their use has demanded care in order to increase production and give a higher quality finish. A series of accepted terms have become generally used to distinguish the classes of cutting oils.

Soluble oils are of two main types: (1) Milky, giving a white emulsion with water, and is usually composed of neutralized sulphurated fatty oil base, mineral oil, wetting agents, emulsion stabilizer and germicide, (2) Clear, which is either based on sulpho-napthalene acid or rosin soap instead of fatty oils and has an increased amount of alkali or germicide present. This gives a translucent dispersion with water.

Straight Oils comprise four main types:

1. Sulphurized mineral oils.
2. Compounded oils.
3. Mineral oils.
4. Fixed.

They may be with or without additions of paraffin, turpentine, white spirit, solvent napthene, and similar hydrocarbons as diluents or solvents.

The further definitions of the actual oils may be summarized as :—

Mineral Oil.—Derivative of petroleum, shale or low temperature carbonization.

Fixed Oil of animal, fish or vegetable origin.

Fatty Oil.—Applied to the animal series of fixed oils—lard, neatsfoot, sperm, whale, horse, woolgrease.

Influence on Tool Life

Cutting oils affect every phase of tooling from chip formation to tolerance. Its most direct influence is on the life of the cutting tool, which withstands for a longer period the abrading effect of chip formation. Also, the high output of frictional and compressive heat which so often leads to tool deformation is neutralized by proper application of the cutting oil.

Finish.—The effect of a suitable cutting oil is to improve the finish of the machined component. The cutting tool is at all times serviced by a film of lubricating oil which eases the break away of the chip, by assisting metal flow.

The microscope, photomicrograph, and electric prism comparator all confirm this, even in the case of free machining metals where no coolant is normally employed.

Tolerance.—As has been discussed earlier, considerations of component finish are indivisably linked with tolerance. The degree of accuracy specified on the blue-print can only be imparted to the component when the tool cutting-edge maintains its keenness.

Delivery of Coolant.—The correct way of feeding the coolant on to the workpiece is a full flow at low pressure. When a relatively small volume of oil is circulating it is unable to limit the heat generated between tool and workpiece below a certain point because its own temperature is excessive.

Selecting a Suitable Coolant or Cutting Fluid

For practical work there are two broad rules which govern the selection.

When the tensile of the metal, depth of cut or cutting speed are such that lubrication is the primary requirement, the use of a straight oil is desirable. Conversely, when lubrication is secondary to the cooling properties, a soluble oil is used. Heavy cuts taken at low speeds need very generous lubrication, while light cuts at low speeds need less cooling and less lubrication.

A shallow cut at high speeds requires marked cooling, and heavy cuts at high speeds must have first class cooling as well as lubrication.

Standardization in the use of fluids must arise both in large industrial concerns, where a system of centralized supply is operative, and in the smaller workshops which need to eliminate complicated store issues in relation to the quantity of machine tools used.

The conditions of supply during the War years demanded certain economies, but such economies must not be obtained at the expense of the surface finish or tool life. It has been found that by making full use of the dilution range, soluble oil will cover the needs of 75 per cent. of operations. For automatics, thread grinding and drilling (high tensile steels only), a medium viscosity mineral/lard oil meets the requirements, while a compound fatty/mineral oil is used for broaching, gear cutting, tapping and screwing.

Effect of Hard Water

One effect which hard water has on soluble oils is to cause separation of the emulsion.

But even when separation is not evident a process of robbing the emulsion takes place through the affinity of calcium and the fatty oil present. The calcium oleate forms and deposits itself as a greasy scum on the machine parts or swarf, and continuously weakens the emulsion until rusting occurs.

Methods of ensuring a soft water supply include the installation of a water softening plant, or the addition of a softening agent to the water before mixing the soluble oil.

Softening agents suitable in proportion to 40 galls. of water are: common soda, 1 lb.; soda ash, ½ lb., tri-basic sodium phosphate, ¼ lb. The method is to dissolve the required amount of alkali in hot water, allow to settle overnight and then draw off the liquid, leaving the precipitated sludge behind.

The action of a fluid on the built up edge of the cutting tool is limited by the wetting power, adherance and film properties of the fluid in use.

From a chemical standpoint the action of some fluids on certain metals is undesirable. For example, sulphurized straight oils may cause tarnish on any copper-rich alloy such as brass or bronze, especially if the oil film is allowed to remain on the finished parts for more than forty-eight hours.

In zinc alloys, the zinc forms a liaison with the oleic acid which is present in sulphonated fatty oils, and zinc oleate is produced in varying quantities according to the alloy analysis. Considerable output of zinc oleate is self-evident and indicates: (*a*) the emulsion is being progressively impoverished by loss of fatty matter, (*b*) free movement of the machine controls being restricted.

A peculiar phenomenon occurs in the machining of certain grades of brass and phospher bronze, used in marine and naval construction work and for sea-going instruments. Many such alloys produce swarf in such a finely divided state that, if a usual non-sulphurized medium viscosity straight oil is employed, much of the brass will remain in suspension, especially in the case of automatic lathes and fine milling operations. The abrasive action of circulating such a mixture is undesirable, and to render the mixture filterable a deflocculating agent must be added to destroy the brass foil colloid.

High Quality Surface Finishing: Experimental

The following notes are a résumé of research, in which the author has taken part, into the application of various theories in order to forward the attainment of the most suitable working surface for the work which such a surface may be called upon to perform.

This research work started in 1935, but a series of events in the War period retarded certain applications but advanced others.

Originally interest was aroused by a series of troubles arising from internal combustion engine big-end bearings, and led in turn to questioning the reasons for the necessity of a "running-in" period for motor vehicles. Knowledge of the actual happenings inside the engine were rather hazy.

When eventually the actual surface of mating parts was considered, experiments were made in order to define the most suitable process and machine with which to produce the desired surface. Meanwhile progress was being made in other directions with regard to the measuring of surface finish.

The machine about to be described is an experimental model, and details of the operation of this machine are discussed at some length.

A sketch of this machine is shown in FIG. 83.

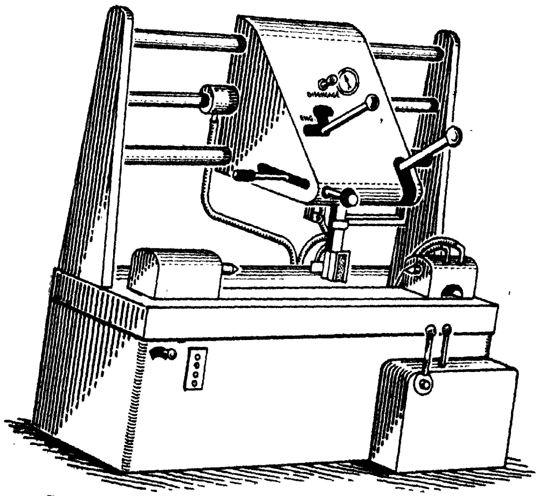


FIG. 83.—Sketch of experimental fine surfacing machine.

The headstock, tailstock and bed construction follow the orthodox method, although the bed is of welded fabricated construction in the place of the usual casting.

The maximum length of work accommodated between the centres is 27 in., while the maximum diameter of the work is 8 in. The headstock is of rigid but simple construction, being driven by a flat belt from an electric motor through a box giving a range of spindle speeds from 14 r.p.m. to 175 r.p.m., the desired speed being selected without stopping the machine, in order to obtain satisfactory results of the process on the workpiece.

The tailstock is of the hydraulically operated type, thus enabling speedy setting and removal of a quantity of similar components, and is fitted with a live centre.

The workhead which holds and operates the abrasive stones is carried on an overhead sliding system operated along the entire length of the workpiece by hydraulic action at speeds ranging from zero to 30 in. per minute.

With operations performed on the outer surface of a cylindrical piece of work, mounted between the centres, the motions of the stone may be from three to seven actions; these motions are carried out with the working face of the stone towards the machine operator. In the case of flat surfaces, such for example as valve or piston heads, the stone is required to turn at 90° to the operator when the workpiece is held in a chucking device.

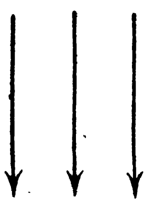


FIG. 84.—Abrasive stone.

FIG. 85.—Abrasive stone.

The abrasive stone must be pivoted in order that it may align with the workpiece, and also to allow the oil wedge principle to come into operation at the correct moment. This pivot point should be ·43 times the length of the stone, measured from the trailing edge of the stone. Although an ample supply of lubricant is required it should be noticed that the rise in temperature of the lubricant is directly proportional to the square root of the load, the viscosity and the surface speed. But this is negligible because the load required is frequently not more than 8 ozs., while the surface speed is rarely more than 60 ft. per min. although the actual motions of the abrasive stone over the surface of the workpiece are numerous, being rotated and oscillated, or what may be termed multi-motion.

This multi-motion, properly applied, produces a surface finish of high quality by virtue of the removal of the fragmented and torn metal left after a commercial machining operation, and leaves a firm, smooth surface of the crystalline construction of the metal.

In order to clarify the working of these stone motions a pencil is inserted in the position on the machine usually

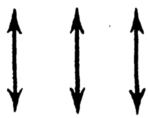


FIG. 86.—Abrasive stone.

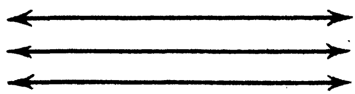


FIG. 87.—Abrasive stone.

occupied by the stone, and this is made to trace a path on a piece of paper wrapped around a cylinder, the results being reproduced in the following figures.

Firstly, the workpiece is made to revolve at a suitable speed, which is selected according to the roughness of the surface (FIG. 84).

The first motion of the abrasive stone is the short up and down motions indicated in FIG. 85. Next comes the reciprocating motion, FIG. 86. Lastly the full length traverse of the stone over the desired length of the workpiece (FIG. 87).

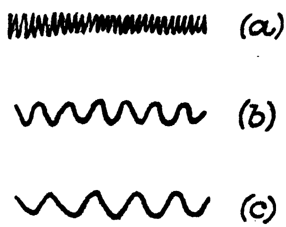


FIG. 88.—This illustrates the action of the stone motions, Fig. 85, in relation to the work revolutions.
(*a*) shows 500 movements at 5 r.p.m.
(*b*) shows 500 movements at 15 r.p.m.
(*c*) is the same at 25 r.p.m.

The ratio of the stone travel to the revolutions of the workpiece creates the resulting area covered by the stone, and varies according to these two factors. The slower the work revolution the more area is covered by the stone, while the higher speed of the workpiece produces less actual area of finish.

Only three graphs indicating this ratio are shown in FIG. 88. It is clear that by adjusting the revolutions per minute of the work, innumerable graphs may be obtained, which may be used as a guide to the most satisfactory speed required for the type of surface being finished.

By adding together all the above-mentioned actions during the operation of the machine, no part of the workpiece surface is left untouched by the light pressure stone.

The true action of the stone, in conjunction with the lubricant, may be considered as "scrubbing" away the peaks left by machining processes or grinding. The basis of the whole processes is carried out in the light of a developed lapping method, but incorporating a method whereby, when the journal or shaft has received sufficient treatment to bring about the action of the oil wedge, it will be in a suitable condition for insertion into the mating part and ensure the continuation of the oil wedge principle under working conditions.

The multi-motions have a pronounced effect on the rate of cutting and the length of time required to process a part, *i.e.* from the time it is inserted in the machine until the oil wedge action lifts the stone from the workpiece may only be a few seconds.

The pressure of the abrasive stones on the component starts fairly high and diminishes as the process near its end. The stone can oscillate at an average of 400 to 500 cycles per minute and the length of each oscillation is $\frac{1}{8}$in., $\frac{3}{16}$in., or $\frac{1}{4}$in.

To calculate the surface speed per minute (given as number of cycles per min. $\times$ 2, which gives the number of passes of the stone per minute). This resultant is multiplied by the length of its movement, giving the total movement in inches.

As an example:

the stone makes 480 cycles per minute.

$$480 \times 2 = 960 \text{ distinct passes per min.}$$

$$960 \times \tfrac{1}{8} \text{ in.} = 120. \quad \frac{120}{12} = 10 \text{ surface ft. per min.}$$

Experiments under varying conditions have not so far revealed any effects which would make the practice of line contact of the abrasive stone with the workpiece any disadvantage, although some quarters advise the use of a correctly shaped stone in the case of cylindrical work.

The stone holder is hydraulically operated to the required pressure against the work, the pressure in pounds being indicated on a gauge in front of the operator, and an adjustment provided alongside to obtain the initial pressure.

The above is a general description of a purely experimental machine, and designers will be able to take up the process from this point in order to design universal machines as well as special purpose types.

The basic requirements may be summarized as follows:

1. Low speed of work in revs. per min.
2. Low speed of bonded stone motions.
3. Ample supply of lubricant.
4. Continuous supply of lubricant.
5. Multi-motion of bonded stone.
6. Gradual increase in speed of work revolutions starting at around 20 surface ft. per minute and increasing.
7. Low pressure of abrasive stone on workpiece.

Some practical results of readings obtained will prove of interest and will indicate the type of finish which may be expected.

The following examples deal only with the micro-surface, and the results are in micro-inches.

Component.	Operation before finishing (Reading in micro-in.)	Final finish reading
24 1 Gudgeon pin	Fine grinding 4·4	0·8
2 " "	" " 4·0	0·9
3 " "	" " 3·5	0·9
38 Plug gauge	Fine grinding 3·0	0·8
42 1 Valve stem	Grinding 21·0	1·0
2 " "	" 23·0	1·5
3 " "	" 22·0	1·0
55 *Surface plate	Hand scraped 31·0	2·0
57 1 Packing disc	Turned 42·0	1·5
2 " "	" 44·0	1·5
3 " "	" 48·0	1·25

*Note: This plate was hand scraped and in consequence there were a number of valleys below the level of the datum which could not be removed during the fine finishing operation. These come within the category of micro-surface.

It is natural to study the results of the machining processes in comparison with each other, and for this purpose a test bar was prepared, the following being results obtained from a test bar of steel 8 in. long and 2 in. in diameter. The bar was proportioned as shown in FIG. 89, and the one inch sections were then processed in the order of: (1) single point tool turning, (2) grinding, (3) honing, (4) hand lapping, and (5) fine finishing on the experimental machine.

The combined results are shown in FIG. 89.

The results outlined above seem to suggest that at last the ideal working surface has been obtained, and indeed this is so—but only up to a point.

By the sure methods of *practical* results certain difficulties arise—not by virtue of the surface, its attainment or the process, but by factors closely related to the surface. The first of these factors is distortion of parts during assembly.

Bearing in mind the sub-microscopic range of surface measurement (SECTION 7) it will be realized that very little distortion between mating parts is required to put one or both parts out-of-round, thus making metal-to-metal contact inevitable. A clear example is found in the case of cylinder bores which may well change shape when the cylinder head is bolted firmly in position, such change of shape probably being only microscopic in value.

Another example occurs in the geometric accuracy of cylindrical parts in which, if checked under a high amplification comparator and rotated, errors in the geometric form may well exceed the value of the surface finish.

The next factor is one which arises when considering lubrication. It has been pointed out (SECTION 3) that in order to ensure constant and adequate oil film lubrication, oil molecules must cling to the metal surfaces in order to support the load and ensure a smooth shear action taking place in the body of the oil.

If a truly mirror finish is obtained with no small indentations then the outer molecules may not adhere to the surface, and the oil film will cease to function, resulting in excessive "galling" of the surfaces.

The above remarks indicate that considerable strides have been made in the removal of the surface fragmented metal under conditions identical with the working conditions of lubricated surfaces. But by practical standards more has yet

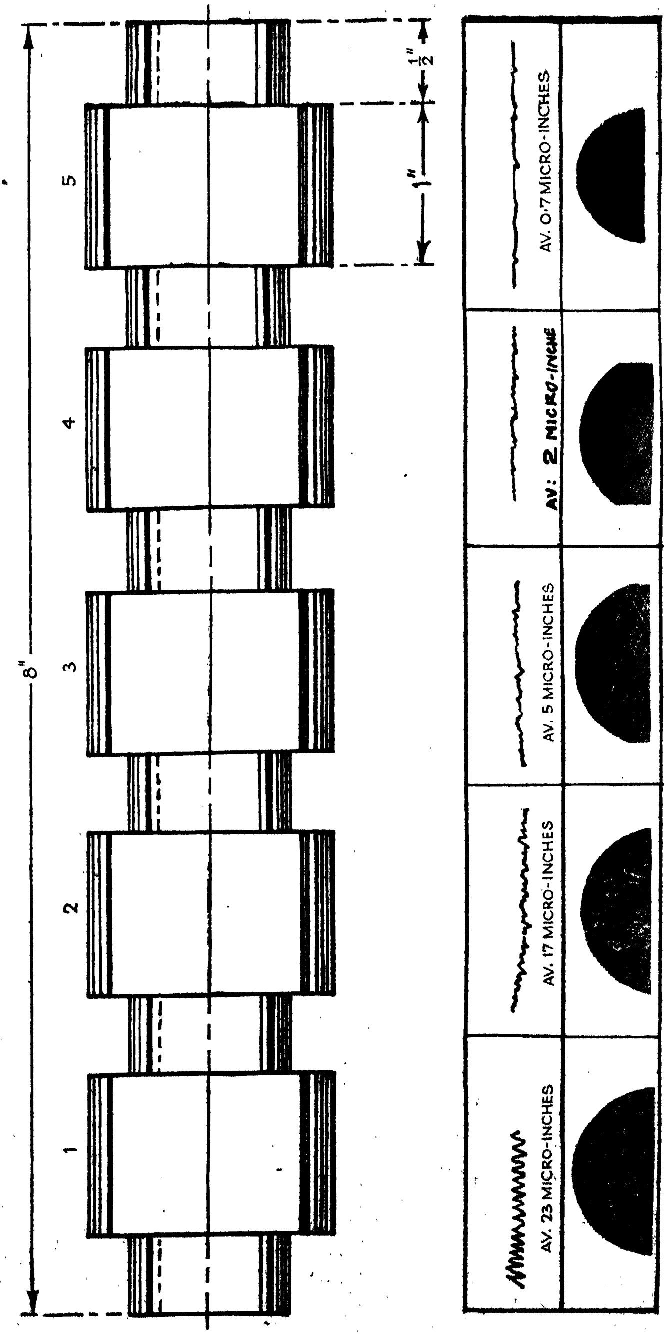


FIG. 89.—Details of a test bar.

1. Diamond turned. 2. Ground. 3. Honed. 4. Lapped. 5. Fine surfaced.

to be accomplished in order that a theoretically smooth surface may be the ideal surface in practice.

But whatever arguments may be advanced by reason of the smallness of surface irregularities and their system of measurement, it has been proved during the production of war mechanical equipment that the surface of mating parts must be seriously considered; and as shown in various parts of this book, things have been accomplished which were at one time considered impossible, largely by the immediate or related effects of the control of surfaces.

This has made it necessary for machine tool designers to produce machines giving even more accurate geometric and dimensional components, and one series of researches made to this end is that with diamond tools for cutting material for aircraft components.

Diamond Cutting Tools

The demand for increased production of non-ferrous component parts for aircraft engines having a high quality surface finish, has increased the demand for diamond cutting tools used in the finish turning operation of these components.

Although a high quality finish can be obtained by carefully prepared cemented carbide type tools, the finish quality can only be maintained for a limited run of work, whereas such a finish can be obtained and maintained with the diamond tools for a longer period.

Certain failures in diamond tools, with resulting poor quality surfaces, led to a series of experiments being carried out which have produced a number of most satisfactory results when viewed from the standard of surface quality obtained in relation to the rate of production.

Details of these experiments and results have been provided by Messrs. British Precision Diamond Tools Ltd.

The experiments were in two main groups, the first being turning, the second boring, and in both cases the test pieces were aluminium pistons of wrought aluminium alloy R.R.59.

The first considerations in the use of diamond cutting tools concern the precision machines, the following being the most important for ensuring a satisfactory quality of surface finish:—

1. The machine must be free from vibration.
2. A precision lapped spindle must run in accurately fitted plain bearings.

3. Accurate endwise location of the spindle.
4. Correct mounting of the machine.
5. Driving motors mounted independently.
6. Endless belt drive with a minimum of gearing.
7. Lubrication of the spindle must be constant.

It will be observed that two of the above demand the consideration of surface finish in their make-up: No. 2 and No. 7.

No. 2 requires that the bearing surfaces of the spindle shall be as nearly perfect as possible both in surface quality and fit to the mating parts, and also to ensure that No 7 is made possible.

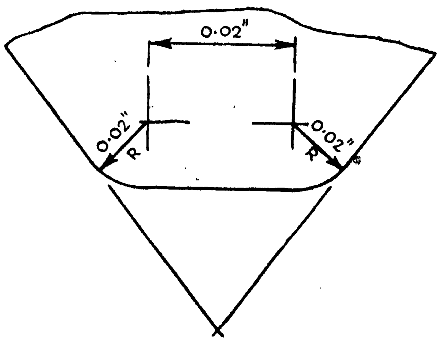


FIG. 90.—Plan of blended facet British precision diamond tools.

The use of surface finish records as described in SECTION 7 enables an accurate check to be kept on varying operating conditions, such records indicating where changes in previous diamond tool cutting practice are desirable.

Diamond Tool.—The development of the diamond indicates that the surface finish obtained bears a direct relationship with the degree of polish and perfection of the cutting edge.

Any deviation from a perfect edge will be reproduced on the surface quality, and will deteriorate progressively as production continues.

In order to ensure this ideal cutting edge, Messrs. British Precision Diamond Tools Ltd. have developed a number of interesting machines of high quality for lapping and processing each diamond.

One of these machines for fine lapping has a specially prepared and carefully balanced diamond impregnated wheel running at approximately 19,000 r.p.m. without vibration.

The machine automatically finds the polishing grain or direction in which it is possible to lap the diamond, the edge form being determined by a generating mechanism controlled by a master former or template 100 times larger than the actual tool tip. This machine is known as the Jearum Mark III Universal Diamond Lapping Machine.

Preliminary experiments indicate that the highest quality of surface finish can be obtained by using a diamond of single facet, having a width of ·020 in. and blended into the side facets with radii of ·020 in. An outline plan drawing of this type of edge is shown in FIG. 90.

Setting of Diamond Tools

To obtain the greatest benefits from the use of blended facet tools, whether for turning or boring, it is essential that they be set truly parallel with the axis of the work. This is made easier by the use of optical equipment.

Speeds and Feeds

Speeds and feeds to be used with any type of cutting tool, in order to obtain the highest quality of finish consistent with good production rates, are very practical factors, which have proved true in experiments with diamond cutting tools.

The cutting speed of diamond tools is the highest speed of which the machine is capable *before vibration sets in*, and this vibration period differs with each individual machine. Above this critical speed vibration will cause chatter on the surface of the workpiece with consequent deterioration of the surface quality.

Feeds for blended facet turning tools, having due regard to the cutting speed and the three cutting forces involved, have been proved satisfactory for production work between ·0014 in. to ·0035 in. with no appreciable difference in surface finish.

Among the conclusions drawn from the research into diamond tool cutting, the following are important:

(*a*) Surfaces can be turned or bored to a maximum surface roughness of under one micro-inch and at the same time produce the required degree of visual finish.

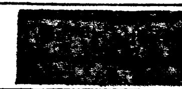
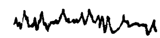
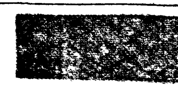
FINISH	SCRATCH	SCRATCH DEPTH MICRO-INCHES	SURFACE SPEED F.P.M.	PRESSURE IN LBS.	HEAT CHANGE °F.	DEPTH OF SURFACE DUCTILITY	MOTIONS USED	SURFACE GRAPH	SURFACE PHOTO MICROGRAPH
TURNED		50 TO •500	50 TO 500	100 TO 1000	600 TO 1000	0·01″ TO 0·128″	1		
GROUND		30 TO 250	3000 TO 8000	100 TO 1000	600 TO 800	0·0005″ TO 0·003″	2		
HONED		5 TO 50	400 TO 1000	50 TO 200	100 TO 300	0·0001″ TO 0·001″	3		
LAPPED		3 TO 10	20 TO 100	2 TO 50	10 TO 80	0·00001″ TO 0·0001″	2		
FINE SURFACE		0·7 TO 7	3 TO 60	0·1 TO 10	0 TO 2	0 TO 0·00001″	3 TO 10		

FIG. 91.—Table of surface comparisons.

(*b*) Set limits to normal production of under 3 micro-inches can quite easily be achieved and maintained.

(*c*) It is very difficult to re-set the tools to the parallel position, in relation to the axis of the workpiece, without optical aid.

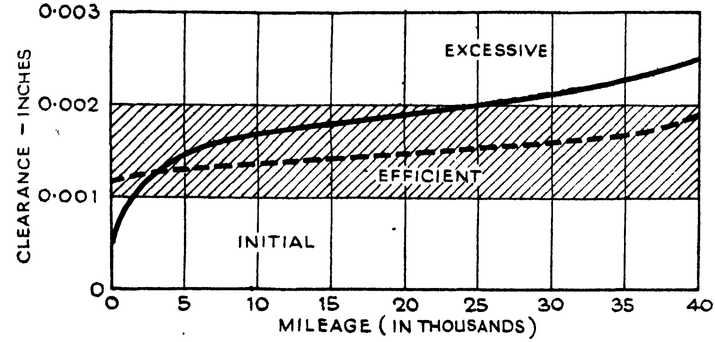


FIG. 92.—Chart of wear in an engine. The engine starts with clearances of ·0005 in. and during the initial "running-in" clearances are increased by wearing away the peaks left during manufacture, thus bringing the clearances into the zone of efficient running. But the initial wear has started a cycle of wear which results in excessive clearances.
By starting life within the efficient zone this will be maintained for a much longer time (dotted line).

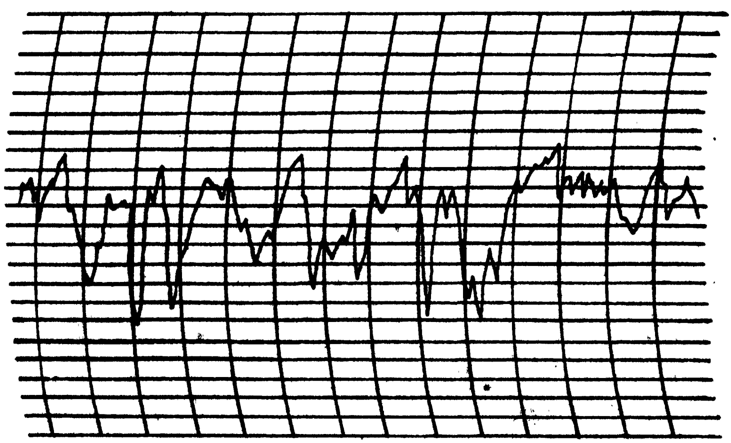


FIG. 93.—Graph of a ground shaft. Average reading ·8 micro-in. Magnification: vertical 20,000, horizontal 200.

(*d*) The experiments have shown the turning and boring tools to be capable of producing a range of finishes between ·7 micro-in. and 4·5 micro-in.

(*e*) The tools must have a perfectly polished cutting-edge. No faults should be apparent at 100 magnifications.

(*f*) The most suitable speed for the machine is that at which it will run without vibration; such speed can only be determined by experiment, as it varies with individual machines, even the same make and type.

A number of recommendations have been presented, the more important of which are:

(*a*) That users of diamond tools be asked to state in micro-inches, with tolerances, the degree of fine finish required (*see* SECTION 7) in order that the correct type of tool may be determined.

(*b*) That for the fine surface finish under 1 micro-inch, the tools should be set precisely parallel to the axis of the work.

(*c*) That cutting speeds should be below the natural vibration period determined by the machine.

(*d*) That whilst coolants do not appear to excercise a very great influence on the results, it is desirable to use soluble oil for the dual purpose of swarf removal and to keep the tool edge free from any tendency to accumulate fine particles of metal.

Summary

As the reader now reaches the end of this book on metal working surface finishes, it is time to review the technique.

This technique, far from being complete, is rapidly improving. It necessitates also a wide knowledge of allied subjects.

The author believes that at present the practical phrase is "the most satisfactory surface"—satisfactory to ensure that the surface does its work in the most efficient manner.

Many improvements have taken place in engineering, particularly during the years 1939-1945, and many ideas have been developed to the ultimate advantage in individual spheres; whilst the development of the working surface has proved an advantage in all mechinical improvements.

Research is going forward in order to attain the complete development of a geometrically correct load carrying surface on a quantity production basis.

The great importance and remarkable effect of surface finish in regard to the load-carrying capacity is indicated in the modern aero-engine, in which the effect of small variations in micro-inch values give outstanding results, thereby demanding the most careful consideration.

That there is a sound case for the production and control of satisfactory working surfaces will be agreed—and the satisfactory surface is dependent upon the work it is called to perform.

The Designer knows from his experience just which standard of working surface is required for the parts of his machine.

The Draughtsman specifies this standard with a plus/minus limit in micro-inches (mu) readings, on his detail drawings.

The Manufacturing Specification Department specifies the desired standards to the machine shops and inspection department.

The Machine Shop, with the aid of suitably constructed graphs as shown throughout this book, is able to produce the standard of surface required with certainty, and also the number of machining operations and finishing operations required to produce the standard and ensure the consistency in any batch of parts.

The Inspection Department is able accurately to check the surfaces and ensure that the specified surface has been obtained and maintained, at the same time being certain that the dimensional accuracy obtained is on the base metal and not over a series of peaks, or waves on the surface.

Scientific considerations of the surface finish will assist the *Research Engineer* to more accurate knowledge of the metals and their construction, their action under the heat and pressures of cutting and abrasions, the surface ductility and the fatigue and physical properties of the metal.

When surfaces are of a known quality of finish, the true action of mating surfaces on oil film can be ascertained with certainty. The element of guesswork is removed from any results obtained over any series of tests in which the value of the surface finish must be one of the considered factors.

By a knowledge of surface finish a true physical and mechanical analysis and specification can be made of any component part.

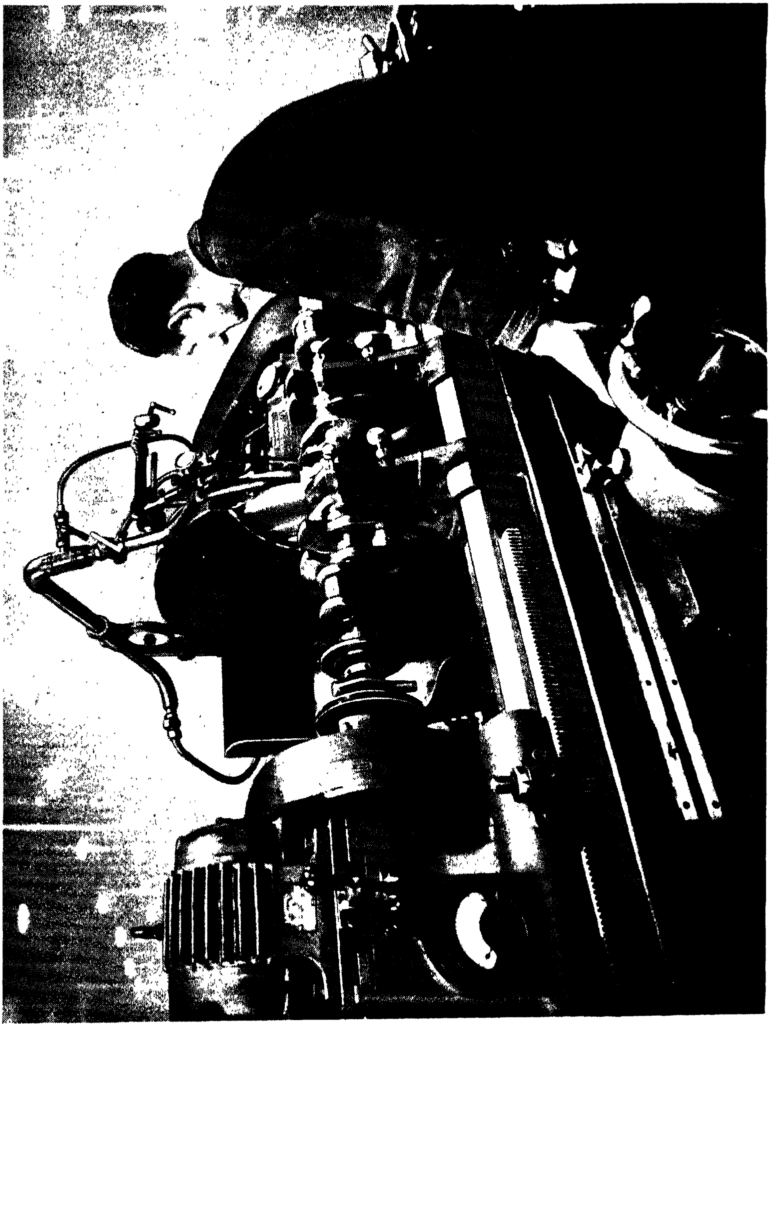
The Manufacturer has the satisfaction of knowing that his components will be accurately matched, whether for assembly on his assembly lines or as replacements later in the life of the machines.

The Customer will be assured of the high standard of engineering precision in the parts which he cannot see, and will not have the initial worry of " running in ".

And so, throughout the vast industry of engineering, surface finish will come into its proper perspective, and engineers become "surface-minded ".

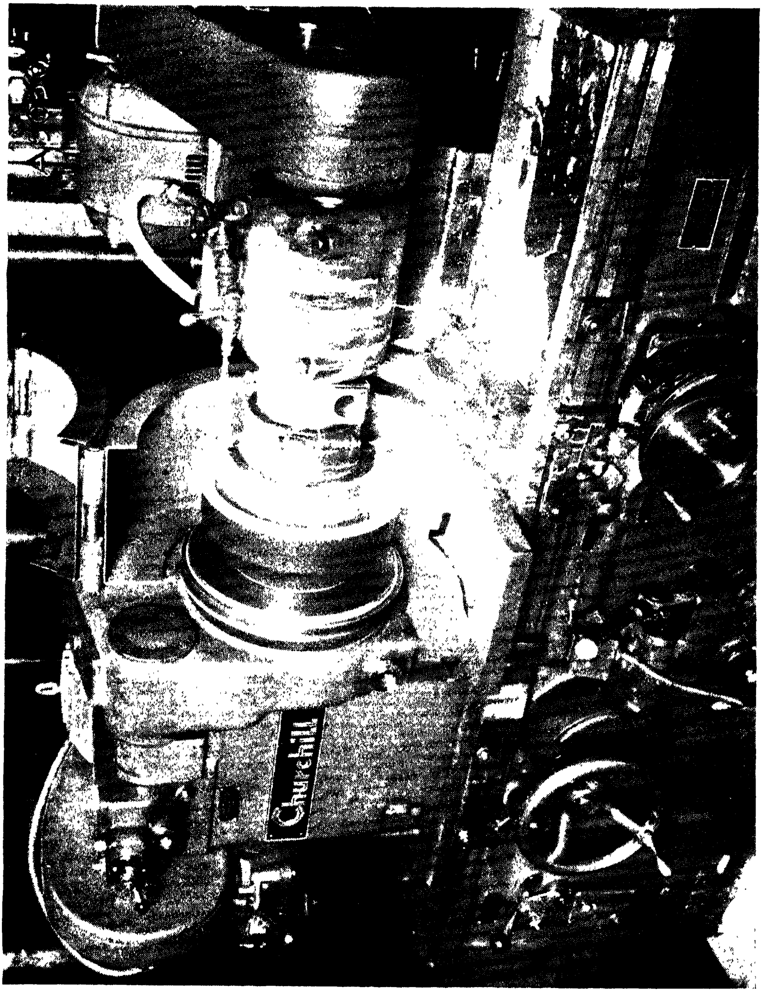
It is the sincere hope of the author that this book will assist all who have any connection with a working surface to a fuller understanding of the evolution which has taken place on the whole subject of surface finishes, and brought this subject to a science, and at the same time help towards an understanding of the many everyday practical facts that must be learnt so that surface finishes may be of the highest quality.

PLATE ONE.



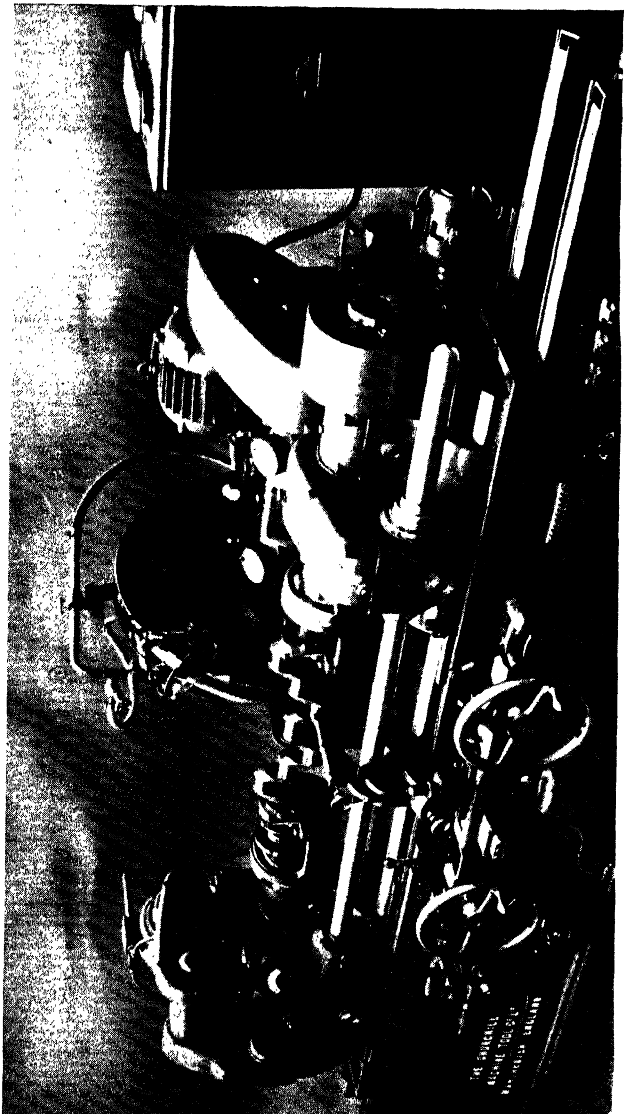
CHURCHILL MODEL "CRM" 20 × 72 IN. CRANKSHAFT GRINDING MACHINE IN OPERATION.

PLATE TWO.



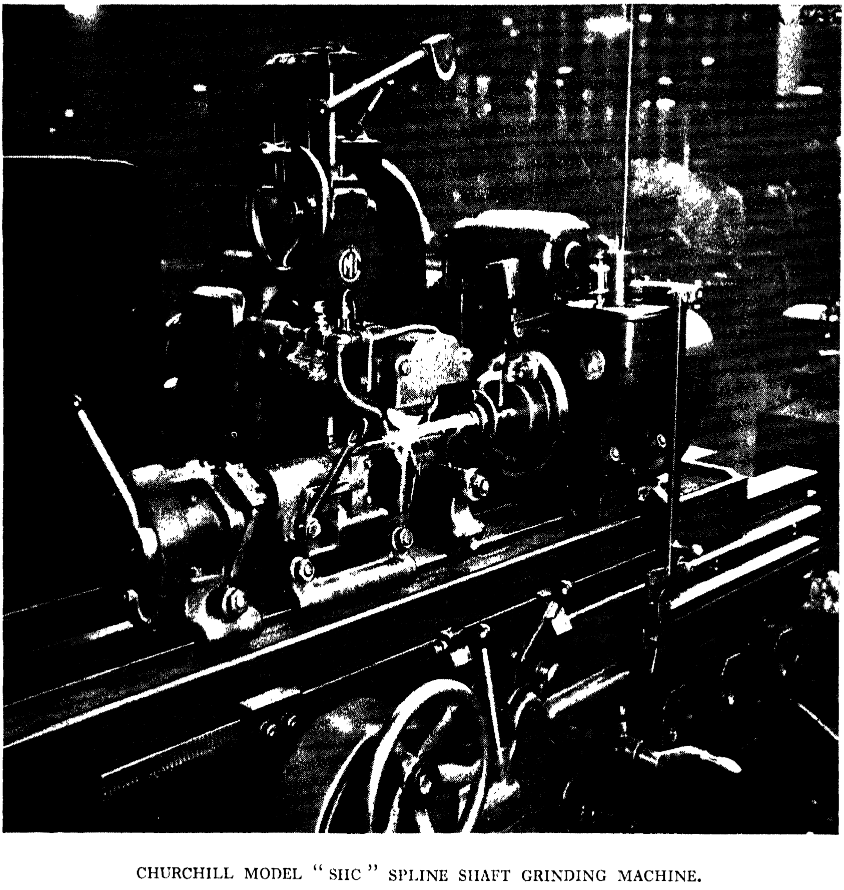
CHURCHILL MODEL "BD" BRAKE DRUM GRINDING MACHINE

PLATE THREE.



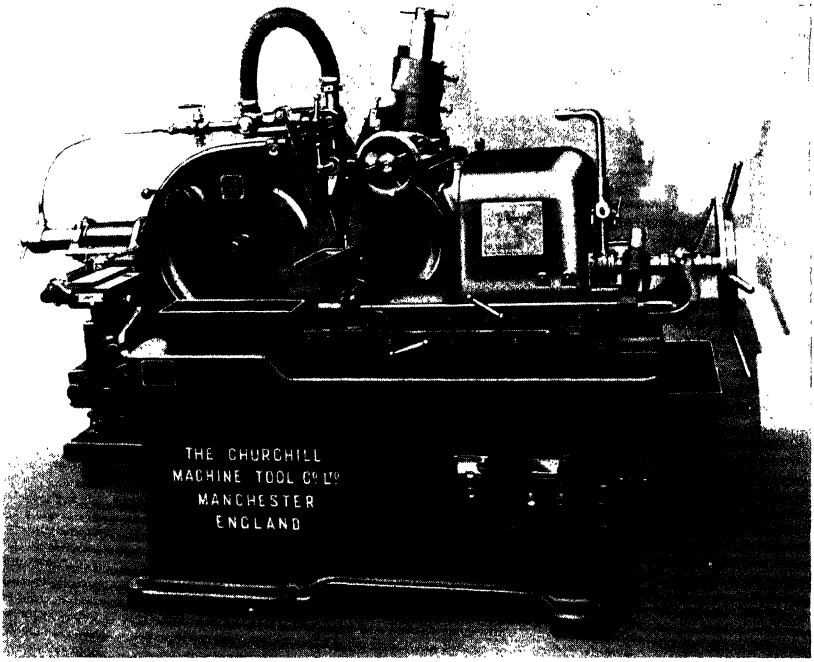
CHURCHILL MODEL "DCH" 20 × 50 IN. CRANKPIN GRINDING MACHINE. MANUFACTURING TYPE WITH DOUBLE END DRIVE

PLATE FOUR.



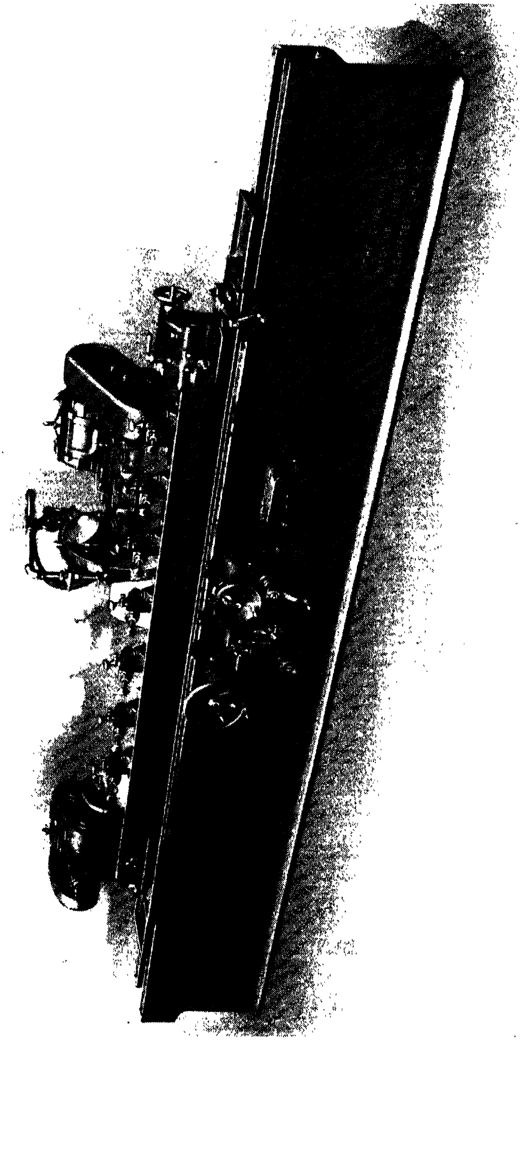
CHURCHILL MODEL "SHC" SPLINE SHAFT GRINDING MACHINE.

PLATE FIVE.

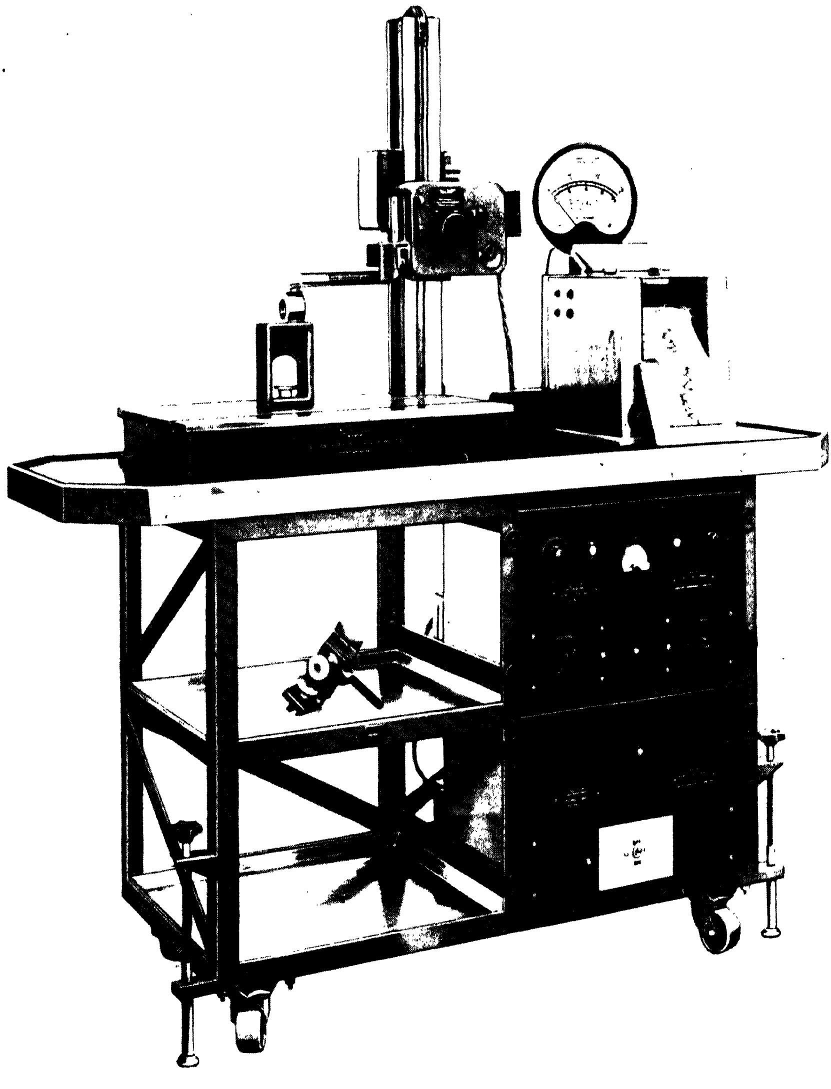


CHURCHILL MODEL "EC" CENTRELESS GRINDING MACHINE.

PLATE SIX.



CHURCHILL MODEL "C" 14 × 108 IN. PLAIN GRINDING MACHINE.



TAYLOR, TAYLOR AND HOBSON "TALYSURF" SURFACE ROUGHNESS MEASURING INSTRUMENT.

Milestones in the Development of Surface Finish

1631	Introduction of the Vernier system of linear measurement by Pierre Vernier.
1769	First boring machine used in the manufacture of cannon, Smeaton.
1775	Watt's steam engine cylinders bored on a Wilkinson machine.
1800	High carbon steels used for cutting tools.
1865	Robert Musket of Sheffield introduced a semi-high-speed steel.
1867	Vernier calipers manufactured by Brown and Sharpe.
1886	Reynolds presented a paper before the Royal Society, on the hydrodynamic oil wedge theory.
1890	Introduction of synthetic abrasive grinding materials.
1896	Introduction of C. E. Johanson's first set of metric gauge blocks.
1898	Chip analysis made of turning operation using a single point tool.
1900	Introduction of high-speed tool steel.
1904	Dr. J. T. Nicolson reported on tool pressures required to ensure chip removal.
1911	Commercial manufacture of gauge blocks.
1915	Commercial introduction of centreless grinding.
1915	Development of stellite for cutting tools.
1916	Development of cemented-carbides for cutting tools in Germany.
1922	Introduction of the first lapping machine.
1929	Introduction of tracer type surface measuring instrument by Gustav Schmaltz of Germany.
1935	Introduction of Profilometer surface measuring instrument.
1936	Superfinish process developed by Chrysler Corporation of America.
1943	Report on the use of diamond cutting tools for quality finishes published.

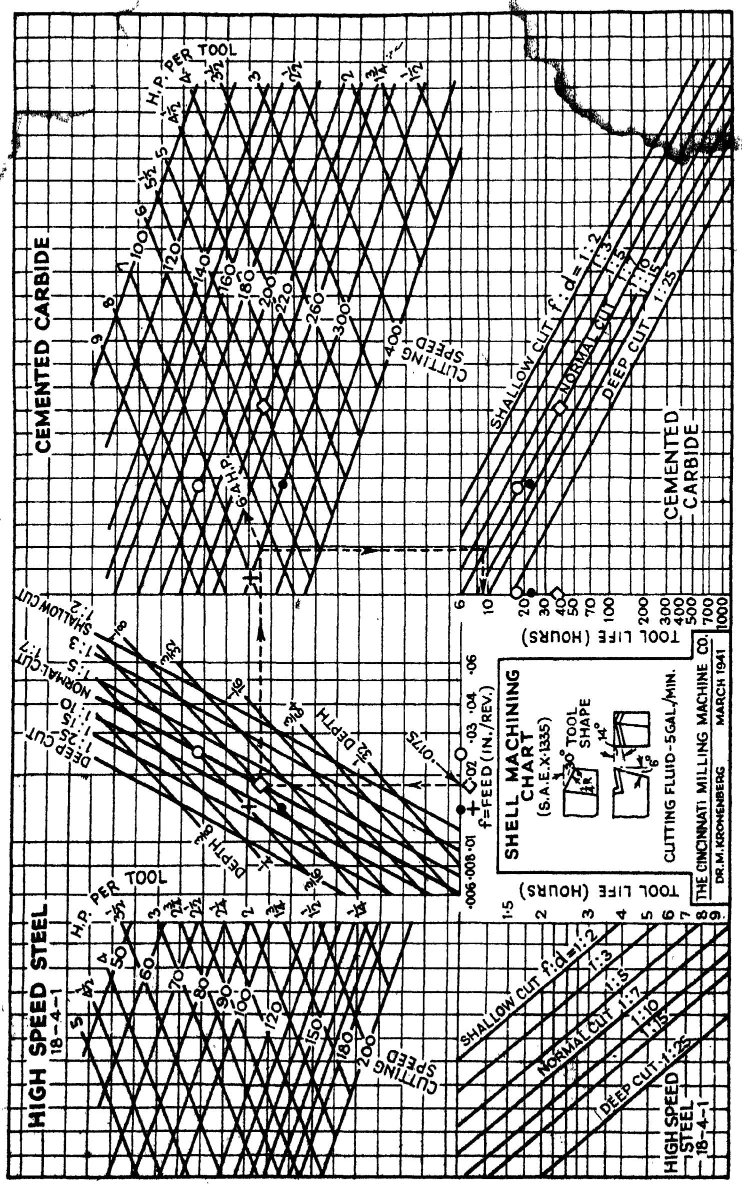


FIG. 94.—Examples of the use of shell machining chart.
(*By coutesy of The Machinery Publishing Co. Ltd.*)

chart applies to the ordinary roughing tool of the shape shown, when used with a cutting fluid supplied at the rate of five gallons per minute. When using carbide tools, it may be necessary, under certain conditions to reduce the rake angle to from 6 to 8 degrees. In this case, the horse-power would increase by approximately 4 per cent.

In the centre of the chart, inclined lines represent the depth of cut, ranging from $\frac{1}{32}$ in. to $\frac{3}{8}$ in. The horizontal scale gives feed rates from 0·006 in. to 0·060 in. per revolution. A second series of inclined lines, with greater slope than the depth-of-cut lines, gives the chip shape ratios (ratio of feed to depth) ranging from 1 : 2 to 1 : 25.

A chip having a depth of twice the feed is called a shallow cut, while a chip having a depth of twenty-five times the feed is called a deep cut. Between these limits lies the normal cut with a ratio of 1 : 7. Chip shape ratios between 1 : 5 and 1 : 10 are the most commonly encountered in practice. The other ratios (1 : 3 and 1 : 15) are included to facilitate the use of the chart in intermediate cases.

The left part of the chart is used in the case of high-speed steel tools, and the right part when cemented-carbide tools are employed. In these two parts of the chart cutting-speed lines and horsepower lines intersect each other. The "ratio lines" for the chip shape are repeated in the lower left and lower right sections as transfer lines leading to the tool-life scales. The chart can be used in different ways, either by beginning with assumed feed rates, or with some other variable. The effect of varying the cutting conditions on the productive factors will be demonstrated later by several examples.

Use of Chart in Case of Assumed Feed Rates

Example 1.—The dotted line on the chart shows an initial example with an assumed feed. The vertical line from a feed of 0·0175 in. per revolution is followed to the line for $\frac{1}{8}$ in. depth of cut. It will be noted that at this point it also intersects the ratio line 1 : 7 (normal cut). From the point of intersection, the dotted line is followed to the right to the selected cutting speed of 300 ft. per minute. Interpolating between the horse-power lines we note that 6·4 horsepower is required for the cut. Following the dotted line downward to the ratio line 1 : 7, in the lower right-hand part of the diagram, we find that the tool life would be nine hours.

Example 2.—*Decreased Feed.* Suppose that it is desired to determine the effect on horsepower and tool life of decreasing the feed to ·014 in. per revolution, keeping the speed and depth of cut the same as in Example 1. The various intersecting points on the chart for Example 2 are represented by dots (·). Following the same procedure as in the previous example, we find that the shape ratio is now between 1 : 7 and 1 : 10, the depth of the cut remaining at $\frac{1}{8}$ in. We further note that the dot on the 300 ft. per minute speed line indicates a decrease in the required power to $5\frac{1}{4}$ horse-power; in the lower right-hand part of the chart we find that there is an increase in tool life to twenty-one hours.

If the production in *Example* 1 is called 100, then the production will be 80 in the present example, due to the reduced feed rate. The horse-power required, however, is reduced, and there is an appreciable gain in tool life.

Example 3: *Decreased Cutting Speed.*—In this example the cutting speed of *Example* 1 (300 ft. per minute) is assumed to be reduced to 240 ft. per minute, retaining the feed and depth of cut given in the initial example. The present example is marked on the chart by a diamond symbol.

Starting at the ·0175 feed rate, and proceeding vertically to the $\frac{1}{8}$ in. depth of cut line, and from there horizontally to the 240 ft. per minute cutting speed line, we find that only 5 horse-power is now required. Proceeding downward to the normal shape ratio (1 : 7) line, we see that the tool life is increased to thirty-eight hours. The production factor in this case, however, is 80.

Example 4: *Decreased Feed, Increased Depth.*—Example 4 is marked by cross symbols (+). The feed is reduced to ·014 in. per revolution and the depth of cut increased to $\frac{3}{16}$ in. The shape ratio is now between 1 : 10 and 1 : 15. Proceeding horizontally to the line for 300 ft. per minute cutting speed, we find that the power required is increased to 7 horsepower, while the tool life would be ten hours.

Example 5: *Increased Feed, Decreased Depth, Decreased Speed.*—*Example* 5 refers to a feed increased to ·024 in. a depth of cut increased to $\frac{3}{16}$ in., and a speed reduced to 200 ft. per minute, as compared with the initial example. The present example is shown on the chart by means of circles (O). In this case, the horse-power consumption rises to 7·5, while the tool life increases to sixteen hours. The production factor, considering the results in *Example* 4 as 100, is 114.

It should be noted that, in this particular example, the increase in the feed results in an increase in production, even though the cutting speed has been reduced.

General Conclusions

It is not assumed that this machining chart represents the "last word", but it is believed that it will be useful, especially if employed as a basis for exchanging experiences in shell machining.

From the examples given, it may be concluded that, in general, the maximum production depends on the horse-power available at the cutting edge, and on the cutting speed the tool can stand. Maximum results are obtained by using high-powered machines at high speeds. The higher the power, the shorter the production time. The power, however, should be used at a speed high enough to permit reasonably low feeds, with relatively small forces and deflections.

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