ELECTRIC WELDING

Its Theory, Practice, Application and Economics

By H. S. MARQUAND

BENN BROTHERS, LTD.
8, Bouverie Street, London, E.C. 4
1920

PREFACE.

IN writing the following manual on the principles of the autogenous welding of metals, we have been influenced by the fact that during the last ten years great progress has been made in the use of both the acetylene and electric arc processes in the industrial world, and there is promise of indefinite expansion of this form of welding because of its sheer worth and efficiency as an industrial process.

It is therefore hoped that a clear and practical exposition of the technique of electric welding will help and enlighten those manufacturers who have installed the equipment in their workshops without the necessary knowledge of correct production and working. We realize how necessary this technical knowledge is when we reflect that electric welding has won for itself a place in the front rank of technical processes, that it is of great and growing importance, and that it is capable of numerous and extremely varied applications in almost every branch of metallic construction and repair.

The fundamental principles of the art of autogenous welding are at present not well understood. This may probably be traced to the fact that it is based upon an old art which was long practised only by a few skilled operators who formed a close co-operation and made it—after the fashion of the old guildsmen—their "Mystery." But, as the proverb tells us, "Fools rush in where wise men fear to tread," and the case of perfecting and cheapening of blowpipe welding thus enabled a number of jobbing craftsmen to commence business as expert welders, although they were without any scientific knowledge of the process; such has also been the case with electric welding. The natural result followed, and the percentage of disastrous failures grew to such alarming dimensions as to begin to throw discredit on the process.

Electric welding proceeded along the same developmental lines as blow-pipe welding, i.e., rule-of-thumb methods went before scientific investigation and testing. Happily we can now announce that during the last four years many scientific authorities, both individually and collectively, have experimented with and analysed the potentialities of electric arc welding, also making a careful study of its successful technique. The data thus provided by scientists and others for practical application which are gathered and collated in this manual will, we hope, consign to oblivion much of the controversial and hazy literature written by blind leaders of the blind on the art of electric welding. The articles which are reproduced in this book were written with a view to disproving such obsolete and faulty instruction by setting down the definite facts which have resulted from thorough investigation coupled with extensive experience and an intimate knowledge of the subject.

For the above reasons it is sincerely hoped that this manual will afford real help to those who are desirous of accomplishing competent craftsmanship. It is self-evident that such a treatise as this cannot claim to be definitive or final, since the technique of electric welding is yet young; but the results already attained are very encouraging, and these technical methods are now based upon a firm foundation of proved experiment, to be further extended by patient study confirmed by practical tests.

The application of electric welding presents astonishing possibilities to the student when once the essential principles are mastered, and some degree of skill attained in manipulating the necessary apparatus. Finally, it is hoped that this unpretentious volume—the product of a busy man's scanty leisure—will help to diffuse that skilled technical knowledge which forms one of the indispensable assets of a great manufacturing State like our own.

H. S. MARQUAND.

June, 1920.

CONTENTS.

INTRODUCTION.

IN view of the prominent position which welding, and especially electric welding, holds in the minds of engineers to-day, when every known science has been harnessed and studied as it never was before in order to speed up production in every branch of engineering, the author is invited to contribute for the interest of all concerned a series of notes on electric welding.

It is always difficult to decide in writing on a practical yet scientific subject just how and what to say and what to leave unsaid. Amidst the abnormal exigencies of the hour it seems futile merely to excite the interest of readers in an all-important subject, or to write from the selfish—for it would become selfish to-day—standpoint of advertisement.

The author ventures, therefore, in approaching the subject of "Electric Welding," to set down some remarks which will be useful and instructive to all those who practise welding in any of its phases, to try and awaken the minds of engineers generally to the great possibilities of welding, and in particular electric welding; and, moreover, to try and stimulate the interest and study of the scientific application of electric welding, the scientific study of a process being only too often relegated as only secondary in importance to the practical study.

It is hoped that the introductory chapters to electric welding proper will help the reader to appreciate more exactly the many difficulties in its successful broad application, and the comparative value of applied electric welding when considering the best and most efficient method of attaining the desired end.

ELECTRIC WELDING: ITS THEORY, PRACTICE, APPLICATION AND ECONOMICS.

CHAPTER I.

METHODS OF MAKING PERMANENT METALLIC JOINTS.

HISTORICAL.

THE working of metals is a science which has been handed up from a very early date in the history of mankind as a time-honoured craft, yet even to-day its rules and methods are surrounded by mystery. The craftsman of old was, as indeed he is to-day, indispensable to the fighting man, and consequently continues to enjoy an honoured and privileged position. It was very soon found that the production of articles constructed of iron or other metals necessitated the joining together of the various parts by a method which for some considerable time has been called welding.

The personal element in welding was always prominent, and no one knew so much about a weld as the man who had made it.

Welding is a critical operation, and it is found that metals can only be successfully united at a definite plastic heat. The range of temperature under which efficient welding with the blacksmith's process is possible is surprisingly small, being only some 100°F. Various mixtures in the form of fluxes have been used by the metal worker to facilitate operations, enhance the flow of the metal, and prevent surface oxidation by the surrounding air.

It is a far cry from the primitive smith's forge to some modern methods of welding, where a machine-made weld takes the place of the fire weld. In the old blacksmith's method the parts to be dealt with are placed in a coke fire, and by means of an air blast, produced by some means from the prehistoric bellows to the latest high-speed motor-driven blower, the metals are brought up to a welding heat when a union between the parts can be effected by bringing them together under great pressure or by closing the joint with machines or hand hammering.

This process of welding metals, although still widely practised, is known to suffer from various disadvantages :

1. The point at which a welding temperature is reached varies greatly.

2. Impurities too often find their way into the joint.

3. The weld itself is sometimes not homogeneous throughout, and a defect is easily hidden, hence considerable knowledge of the peculiar characteristics of the various metals and great skill is necessary with this class of welding.

Although the following methods that the author ventures to describe are entirely different, and without doubt for certain classes of work produce far superior results to any that can be obtained on the blacksmith's forge, electric welding is not expected to replace blacksmith's welding. On the contrary, the electric process has a distinct field of its own, and, as will be pointed out later, many ramifications of welding can be successfully carried out which the modern blacksmith could not accomplish by any means.

Before considering in detail any one system of autogenous welding, and in order to appreciate thoroughly its advantages and possibilities, it is useful to examine briefly all other practical methods for effecting permanent metallic joints, to know and apprise their several characteristics, their applications, their advantages, and their faults.

It must be admitted after such an examination that each of these practical methods has its own particular field of value, each has its defined legitimate application, its defects and its advantages. They complement each other rather than replace each other ; each has its own particular claim to be best suited to obtain certain desired results under given conditions and requirements.

SOFT-SOLDERING.

Soldering is generally applied for joining together pieces of more or less thin metal with the ultimate object of obtaining an air-tight or water-tight joint more often than one of strength.

Soft solder has a very much lower strength than the metals to be joined together; its tensile strength, elongation, etc., is very low, and in consequence to ensure a firm joint it is necessary to make the contact surfaces of the joint as large as possible, so that tightness at the joint is obtained by adhesion, as in the case of gum or pastes in joining paper, etc.

When, however, the contact surface cannot be increased sufficiently to obtain the required resistance at the joint by adhesion, it is necessary in some way to add solder, and thus thicken up the joint in order to increase the resistance; for example, in the joining of sheet tin cases or tanks, the joining up of lead pipes, etc.

Soldering is applied for the joining of lead plates, etc., tin, zinc, galvanized plates, and sometimes copper, brass, or aluminium, but only when the joint has not to stand any serious strain or vibration.

The fusing point of the solder used is invariably lower than that of the metals to be joined; the joint is much weaker than the original metal and really only constitutes an adhesion and not in any sense an alloy.

To ensure an efficient joint it is important and necessary to clean thoroughly the surfaces to be joined, using a flux to remove or prevent any oxide forming during the process of soldering. The melting point of solder varies from 160°C., or even lower in the case of a very fusible solder, to 245°C. in the case of plumbers' solder.

Plumbers' coarse solder contains 1 part of tin to 3 parts of lead; the softer and finer the solder the less proportion of lead contained in it. The very fusible solder contains a proportion of bismuth up to 25 per cent.

The fluxes generally used are resin, chloride of zinc, colphonium and sal-ammoniac.

BRAZING.

Brazing, sometimes termed hard soldering, differs from soldering in that a metallic cement is used which melts at a high temperature, and possesses a high mechanical resistance, which cement is called brazing metal.

It is necessary to heat strongly the contact surfaces or edges to be joined and to clean them with a suitable flux, melting also at a high temperature.

The brazing metal is usually applied mixed with the flux in the form of a powder or fillings. Its melting point is a little below that of the metals to be joined, so that when heating the piece to be brazed to a high temperature the brazing metal melts and adheres to the edges to be joined and really forms an intermediate alloy; the final joining being obtained after cooling.

As in soft soldering, the larger the contact surface of the joint the greater will be its efficiency.

Brazing necessitates the use of a forge or blow-pipe. The use of a forge is costly, and not always convenient. However, in using the blow-pipe for brazing, considerable skill is necessary, as, the heat being so strictly local, the metal tends to be burned, especially in the case of brass. However, the blow-pipe providing a high temperature enables a quick heat to be obtained, and the use of a less fusible brazing material, which makes the joining of cast iron by brazing quite possible.

Brazing fails to fulfil the perfect conditions required for perfect joining owing to the following disadvantages:

The part brazed has different chemical, physical, and mechanical properties from that of the original part, and hence electrolytic action sets in and disintegrates the joint; also the successful operation is dependent upon too many factors, apart from the human element.

Nevertheless, the brazing process is very largely used for repair and repetition work.

THERMIT WELDING.

This process is applicable to the joining of iron and mild steels of heavy sections.

A mixture of powdered aluminium and iron oxide is burned, and the temperature of combustion is very high, sometimes as high as 3,200°C. The aluminium unites with the oxygen, forming alumina, and the free iron then accumulates in a molten state at the bottom.

The pieces to be joined are placed in position, and a mould built round and filled with the mixture, which is ignited. The resultant high temperature melts the edges to be joined, and an autogenous weld is obtained.

This process, though yielding good results, requires costly materials and necessitates a lengthy preparation, and hence has only been used for very important, or repetition, work. It has been chiefly applied to the bonding of steel rails and the repair of very large castings.

The Thermit process of welding is now largely replaced by oxy-acetylene or electric arc welding.

RIVETING.

The method of the joining together of plates, etc., by overlapping their edges and riveting the two thicknesses together, or by placing the extreme edges in contact and holding them thus by riveting each to a common butt strap or cover plate, will no doubt be used for some time to come. The method is carried out where great strength is required or when autogenous welding cannot easily be applied.

The resistance of a riveted joint depends upon the adhesion of the overlapping plates or upon the rivets themselves, which perform the function of a kind of link. To obtain a good adhesion the rivets must be previously heated, for when rivets are put in cold up to ½ in. the adhesion is practically nil.

The resistance of riveted joints is incapable of withstanding great shocks, with the consequent result that a permanent set or deformation takes place; the plates become more or less distorted and get a certain amount of play, which is increased with each new shock or with intermittent vibrations. Air and moisture intervene between the plates, and corrosion is set up which rapidly weakens the plates, and even causes their total destruction.

Alternate expansion and contraction produce the same effects as a series of shocks ; hence a joint which is subjected to widely varying temperatures, such as the riveted joints of a boiler, or, as found in many tanks, the binding power of the rivets is rapidly lowered, and this leads to inevitable and destructive results.

Nevertheless, for well designed and well made riveted joints the mechanical efficiency is fairly good and reliable.

In general practice well-designed joints should give the following mechanical efficiencies:

Single-riveted joints, 50 per cent. to 60 per cent. of the strength of the solid plate.

Double riveted, 70 per cent. solid plate.

Treble riveted, 75 per cent. solid plate.

As will be seen later, a combination of a riveted and autogenous welded joint is now often resorted to with excellent results, both as regards strength and reliability, and also as a means of largely increasing the life and effectiveness of the joint by stopping the inroads of internal corrosion and increasing the elasticity of the joint.

AUTOGENOUS WELDING WITH BLOW-PIPE.

Autogenous welding, strictly speaking, is the process of effecting a permanent joint by melting the metal under the action of the flame of a blow-pipe. Thus, actually, all welds made with the forge, water gas, electricity, or the blow-pipe may be termed autogenous, since they have been obtained without the interposition of a metallic cement, whose physical and chemical properties differ from those of the original metals welded.

Blow-pipe welding consists in fusing the metal by the action of a hot flame of appropriate temperature and uniting by the addition of a metal of as far as possible the same composition. The blow-pipe is the instrument in which the gases are mixed and the flame produced and projected upon the metallic parts to be welded.

Autogenous welding by means of a combustible flame has been known and applied for many centuries; yet comparatively only in modern days has the welding of metals of a high melting point been successfully achieved.

By this method the Egyptian, the Greeks, and the Romans obtained very considerable skill in the working of the soft metals. A flame of sufficiently high temperature was not provided until the commercial manufacture of oxygen permitted the use of this gas for the production of flames of high temperature.

Consequent upon the industrial manufacture of oxygen many flames using this gas as one constituent have been tried, such as:

The oxy-hydrogen (oxygen and hydrogen gas).
The oxy-coal gas (oxygen and coal gas).
The oxy-benzene (oxygen and vapour of benzol).
The oxy-acetylene (oxygen and acetylene gas).

The last-named flame is now highly developed and widely used in industrial work to-day. Its theory, practice, and application is far beyond the scope of these articles, and, indeed, much excellent literature has been published on this phase of autogenous welding. Suffice it that the general remarks on electric welding apply also to gas welding, and, speaking generally, the field of application of gas and electricity in the working of metals is common to both. Both claim the advantage over the other. However, it is not the purpose of these articles to reopen this controversy, but to try and stimulate knowledge and interest among engineers generally in the great possibilities and ever-widening field of application of autogenous welding.

ELECTRIC WELDING.

Consequent upon the progress of electricity in the service of man, attention was turned to its use in heating metals to be welded. Space does not permit of description of the numerous experiments in this direction, neither can a detailed history of the gradual progress of electric welding be given here. It is sufficient to say that electric welding is no longer a novelty; rather has it become a fine art.

The first to attain success in the utilization of the heat of the electric arc for the purpose of making a weld was a Russian engineer named Benardos, who used a carbon pencil to form the positive electrode forming an arc with the object to be welded as the negative pole of the circuit. Recognizing the disadvantages of the original Benardos system, another Russian engineer called Slavianoff attempted to overcome them by substituting a steel or iron electrode for the carbon one, the electrode being fused together with the part to be welded by the heat of the electric arc. Inspired by these early experiments, the advent of the twentieth century found an increasing band of workers in many lands engaged upon this evasive problem of arc welding. The difficulties to be surmounted were considerable, involving the production and control of the electric current, the protection of the weld from contamination, the choice of a satisfactory metal electrode, and the production and application of a suitable flux. It is thus evident that the practical welder was dependent upon the engineer and the chemist.

Although many engineers in this country attained a fair measure of success in the application of modern electric arc welding, it was first applied to practical use on the Continent, and its various ramifications were very jealously guarded as trade secrets.

Mr. R. S. Kennedy, who had been engaged in experimental work in London, early in 1910 formed a company to carry on the process in Great Britain ; this company now has plant stationed in all the principal ports. Resulting from prolonged research and a careful study of the peculiar characteristics and requirements of electric arc welding, machinery and equipments for its application have been very considerably improved both as regards design and operating costs, and as a direct result the quality of the finished weld, and also the rapidity with which work can be effected by this process, has materially advanced.

While many engineers devoted their energies to perfecting electric arc welding, another group studied and experimented along an entirely different principle, known generally as resistance welding. Here, again, advantage was taken of the inherent property of the heat developed by an electric current, which was harnessed to accomplish the same end—namely, to weld two metal parts together. This valuable property of electricity having once been grasped, progress developed upon the line of devising apparatus best suited for applying it to certain classes of work, and many manufacturers concentrated their attention more or less secretly on the perfecting of special types of welding machines.

Even to-day, though much less so than in the past, trade reticence has had very considerable effect in checking the progress of electric welding, for many firms who have installed electric welders have found that with their help much could be done that was impossible before, or that many processes can be completed in a much shorter time, and that operating costs could be considerably reduced ; consequently they jealously guarded their trade secrets. This was all right from their own point of view, but most harmful to the electrical interests involved.

However, that era in industry has nearly passed away, and, like many other secret processes, electric welding is coming into its own, with the result that electric welders are now used in countless manufacturing processes, many of which would be commercially impossible without resort to electric-welding.

CHAPTER II.

THE PROPERTIES OF METALS CONSIDERED FROM THE WELDING POINT OF VIEW.

INTRODUCTORY REMARKS.

BEFORE progress can really be made in the ultimate results and range of application of electric welding, it is essentially necessary to understand thoroughly what is happening in making a weld, to study the physical and chemical phenomena produced in a metal in fusion under the action of the heat, such that the finished work will be left as perfect as is possible.

We shall try and treat this broad subject as simply and concisely as possible, and we venture to think that it is essential that the would-be welder himself should study it with us, thoroughly digest it and ponder thereon, so that he unconsciously takes it into account in the practice of his work. It may safely be said that the greater the welder's knowledge of metallurgy and the many and various phenomena which control and influence his weld, the wider will be the scope of welding he can accomplish and the higher will be the degree of skill he can attain.

MELTING POINT.

Welding consists in making the metals pass from the solid state into the liquid state and in causing their ultimate union during resolidification.

All metals have their particular melting temperature, called their " melting point." When two or more elements whose respective melting points are known are chemically or physically united to form a new composition or alloy, the melting point of the new alloy will differ from that of each of its constituents, according to the percentage of each contained in the alloy. Most commercial alloys are now of standard composition and have acquired a definite name ; hence, we can draw out a very fair and complete table of melting points for our guidance.

It is not sufficient to know that the difference between the fusion points of, say, lead at 325°C. and iron at 1,500°C. is so great, which is common knowledge; the difference between the melting points of cast irons, steels, copper, brasses, etc., should be equally well known by the practical welder.

TABLE 1.—*Melting Points of the Principal Metals and their Alloys.*

——	Deg. Cen.	Deg. Fah.	——	Deg. Cen.	Deg. Fah.
(*a*) Lead........	325	630	(*j*) Red copper ..	1,050	1,920
(*b*) Zinc........	410	870	(*k*) Nickel	1,400	2,550
(*c*) Aluminium..	650	1,200	(*l*) White iron, cast	1,200	2,010
(*d*) Bronze	900	1,650	(*m*) Grey iron ,,	1,200	2,190
(*e*) Brass	950	1,740	(*n*) Hard steel	1,400	2,550
(*f*) Silver	950	1,740	(*p*) Mild steel ..	1,450 1,500	2,640 2,730
(*g*) Platinum ..	1,775	3,230	(*q*) Iron	1,500	2,730
(*h*) Gold	..	2,100	(*r*) Antimony	..	1,166
(*i*) Tin	..	449			

TABLE 2.—*Specific Heat of the Principal Metals and their Alloys.*

(*a*) 0.031	(*g*) 0.032	(*m*) 0.126
(*b*) 0.09	(*h*) 0.032	(*n*) 0.116
(*c*) 0.212	(*i*) 0.056	(*p*) 0.114
(*d*)	(*j*) 0.092	(*q*) 0.113
(*e*) 0.094	(*k*) 0.109	(*r*) 0.051
(*f*) 0.056	(*l*) 0.130	

When considering the melting temperatures of the various metals it is necessary to take into account the total heat of fusion; that is to say, the quantity of heat required to bring a unit quantity of the metal up to a certain temperature increase. The specific heat varies with different metals, as can be seen from Table 2.

Again all metals do not conduct heat equally; copper, aluminium, iron, and lead, for examples, have widely different properties of conduction. The conductivity of a metal plays a large part in welding. The loss of heat while making the weld will be more or less according to the metals welded. Moreover, it influences and complicates the phenomena of expansion and contraction, of which we shall speak later, and which extends itself over a greater or lesser area, more or less rapidly, with entirely different consequences; and, last but not least, in proportion to the conductivity the metal in the neighbourhood of the weld is subject to more or less change in its physical and mechanical properties.

It is thus evident that the welder must take into account the conductivity of the metals which he has to join. For example, although the melting point of copper is greatly below that of steel, the welder will require the same power or intensity of heat for the same thickness of weld, for the copper will conduct away the heat put into the weld so fast that it would otherwise take too long to bring any point up to a welding heat. Nor should the weld be effected until the surrounding part is at a dull red heat, so that the metal in fusion shall not be solidified too rapidly owing to the drawing off of the heat by conduction.

Again, cast iron has a much higher melting point than copper, and one might infer that a heat of greater intensity would be required than for copper or aluminium ; but, as a matter of fact, it is quite the opposite, for cast iron is such a bad conductor of heat that if an intense heat is applied at any point, the effects of expansion and contraction immediately take place, due to the sudden difference in temperature between adjacent parts, with often disastrous results. However, as will be shown later, this difficulty can be provided against.

OXIDATION.

When free oxygen attacks metal it combines very readily with the metal, forming a new chemical compound, called the oxide of the metal, and this oxidation is enhanced with increase of temperature, especially so if oxygen is evolved in the process of the welding.

While executing the weld the metal can be oxidized in three ways : by contact with the oxygen in the surrounding air, by the oxygen set free from either of the metals under the action of the heat, or from impurities, or, thirdly, if a chemical flame is used it may very easily contain an excess of oxygen. Again, water vapour can produce the same effect as free oxygen.

Those bodies which tend to give up their oxygen are called

" oxidizing agents," while those which tend to extract it from other bodies are called " reducing agents."

The close study of the oxides of the various metals that are welded is absolutely necessary, since due to their presence and behaviour a weld can be totally spoiled, although the finished weld may appear perfectly sound.

Now, as it is nearly impossible to prevent oxide forming when making a weld, it is of great importance that all the possible ways of neutralizing the oxide and cleansing the weld of its presence should be known to the welder. Hence we shall investigate the more common metallic oxides and describe their fundamental differences.

Firstly, then, the oxide of the metal may be lighter or heavier than the metal itself, and consequently can float on the surface of the molten bath of the weld, or it may remain hidden in the interior of the weld.

Again, the oxide of the metal may fuse at a higher or lower temperature than the metal itself, and accordingly this may make it more or less difficult to eliminate the oxide from the weld.

Another peculiar property of some oxides is that they are directly soluble in the molten metal in varying proportions, which, on cooling, separate from the mass, often in the state of an alloy.

In the welding of metals it is apparently necessary first to prevent, as far as possible, the formation of oxide ; secondly, to avoid imprisoning the oxide in the weld ; and, thirdly, to dissolve or separate the oxide formed by means of a reducing agent or a chemical flux.

It is well known that there are incorporated in certain metals largely used in industrial constructional work certain foreign elements destined to alter the physical state of the metal and to give to it certain properties to suit particular specific requirements. For example, steels may contain the elements manganese, carbon, silicon, nickel and various others ; brass and similar alloys contain zinc and tin.

These bodies, whose presence is of vital importance, are present in only small quantities, and can easily be burned or volatilized under the action of the great heat of the weld. The consequence of this phenomenon is often noticed, and hence certain alloys which become impoverished after welding are blatantly said to be unweldable. This is far from being a correct presumption. It certainly is too often the case, but solely because the welder has no technical knowledge of what he is endeavouring to do.

A number of the elements can oxidize directly, or through the reduction of the oxide of the metal formed during the process of welding, and undergo true combustion in the course of welding.

When these elements in an alloy are destroyed, the line of weld becomes impoverished, and in consequence a change in that state of the metal in relation to the remainder of the article is obvious.

The welder, by knowing the construction of the alloy, can guard against this weakening of the weld by manipulation or by using a filling material containing an excess of the element which is eliminated due to volatilization or burning, and thus compensate the loss by adding an equal portion.

Iron and its alloys usually contain carbon as one of their chemical constituents in the proportion of 0.05 per cent. in mild steel or 1.5 per cent. in extra hard steel, and in cast iron the percentage of carbon often runs up to 4.5 per cent. This carbon can be either destroyed or affected by direct contact with the oxygen of the surrounding air ; heated carbon having a great affinity for oxygen, in both cases the result is a decarbonization of the metal. Again, iron has a distinct tendency to absorb carbon and to become carbonized ; hence, if the weld becomes decarbonized, or if it becomes carbonized, a bad weld results, and hence, again, the nature of the metal in the weld must be carefully considered.

A very prevalent cause of blowholes in a weld is due to the ability of some metals to dissolve gases in solution and to render it up on cooling. At the instant that the molten metal changes from the liquid to the solid state, the absorbed gases are given up, resulting in blowholes in the weld, which are a great source of disappointment and worry where the weld has to stand fluid pressure.

Furthermore, the very rapid change from the liquid to the solid state when direct heat is interrupted results in bubbles of absorbed gas being incorporated in the mass near the surface, again resulting in blowholes, and consequently weakening and often completely upsetting the mechanical soundness of the weld; but here, again, a remedy can be found when the welder understands the cause and effect.

EXPANSION AND CONTRACTION.

The wider the welder's knowledge of the elusive laws of expansion and contraction the greater will be his measure of success in welding and the broader his scope and range of application. Bodies expand to varying degrees under the influence of heat, with a consequent increase in volume, while on cooling they again return to their original dimensions.

The amount of expansion per degree rise in temperature is termed the "coefficient of expansion." Metallic bodies have a relatively high coefficient of expansion, and are particularly susceptible to change of temperature. Thus, it is plainly to be seen that so long as a metallic body as a whole is subjected to a perfectly uniform cycle of expansion and contraction no ill-effects are likely to result; but if suddenly heated or cooled at a point locally the metal at this place tends to expand or contract with incalculable force, and hence it will either crush the surrounding metal or break away from it.

No force can stop this inherent action, and it is useless to try and oppose it by means of mechanical clamps of any device. It is necessary in some way to forestall this action by preheating the complete article previous to effecting a weld, by allowing for free play in preparing the job before welding, or by creating an opposing force by the simultaneous heating or cooling of opposing parts.

To the experienced welder there are a hundred ways and means of defeating this enemy. No definite advice can be given, as the treatment depends on the metal and each piece of metal according to its shape and dimensions. Nevertheless, it may be said, to the encouragement of the ambitious, that rarely does a case arise for which there is no solution.

In some metals this troublesome effect of internal strains has a more far-reaching result than in others; for instance, those metals possessing high percentage of elongation and elasticity are not easily distorted to destruction, and often the effect of the expansion or contraction can be obviated by afterwards working the metal. On the contrary, those metals which do not possess sufficient elongation and elasticity break like glass when heated locally, and require careful handling and due preparation.

When the expansion can take place in all directions, welding from cold is fairly safe, if not carried out too suddenly ; but when it is prevented by angles, rings, lugs, etc., and of widely differing thicknesses, the result may be disastrous if great precautions are not exercised. The rupture generally takes place at the point which tries to stop the movement, and it will be found that the effects of expansion will take place at any such point, while that of contraction is generally localized in the near vicinity of the weld.

We shall explain this phenomena more fully when dealing with each metal, and we shall detail the execution of various classes of work which will, perhaps, be the best guide.

THE MECHANICAL PROPERTIES OF WELDS.

What is generally understood as the mechanical properties of metals—namely, their hardness, tenacity, ductility, malleability, strength, etc.—vary with their temperature, their molecular structure, and localized stresses set up at certain points due to a number of causes brought about during manufacture or subsequent working.

The texture of a metal considerably influences the mechanical properties. Most metal workers are familiar with the effect of hammering, tempering, annealing, etc., on the crystalline texture and uniformity of the metal.

A diligent study of these modifications is essential to the successful toolsmith. For instance, he knows that by subjecting the edge of a cutting tool to a certain and definite heat treatment he can make the tool stand up to a certain specific class of work, and at the same time he knows that the shank of the tool, while of the same original metal, now has properties quite different from those of the working part.

In the same way, the portion of metal which has become molten in the weld, even under the best possible care, rapidly cools, and is generally to a greater or lesser extent different in mechanical properties from the surrounding metal. Again, the parts in conjunction around the weld may have been influenced by the heat, and no longer be in the same physical state as before the execution of the weld.

It is well to realize that the tenacity of certain metals, however great, becomes practically nil when at a temperature yet below the melting point. For instance, in the case of copper and aluminium, and certain special steels, fracture after cooling is much more common than in others. However, this phenomenon will be explained more fully in the following paragraphs on the welding of such metals.

Again, it must not be forgotten that internal strains on contraction, though they may be insufficient to cause immediate rupture, are none the less existent, and the line of weld and its neighbourhood may remain permanently strained, and thus very susceptible to shock, often resulting in far greater damage than the damage originally repaired.

In some cases these after-effects have little or no consequence. The working conditions of the welded article are not such that the weld is put to a very severe test of homogeneity and mechanical points. In other cases, however, and it is best as far as it is possible always to assume this case, the line of welding must be perfectly homogeneous, ductile, and of maximum tenacity; also the complete structure must be in equilibrium and in an unaltered physical state.

This last paragraph is perhaps of greater importance than all the foregoing, as it really embodies all the precautions set out in the previous paragraphs, and really concerns the ultimate and lasting result of the welded repair.

In addition to the above precautions, which can and should be taken during the operation of welding, mechanical and heat treatment can be applied, such as cold hammering, annealing, tempering, etc. It is incumbent upon every first-class welder to know the influence upon his metal of these treatments, and to apply them judiciously whenever necessary and possible.

It is obvious from the foregoing that it will be advantageous to add to the bath of fusion produced in the execution of a weld certain elements calculated to combat the various phenomena, and to neutralize the chemical effects which would be detrimental to the successful conclusion of a weld, and to enhance as far as possible the chemical, physical, and mechanical properties of the structure in and around the line of welding.

Generally speaking, it is most difficult to persuade the practical, and usually non-technical, welder of the necessity of adding special materials and products unless he finds it impossible to execute the weld, or unless the advantages are distinctly apparent. Moreover, superficial examination of a weld too often fails to show any fault, and it even has the appearance of being a perfectly sound and clean weld; yet the same weld may be far from homogeneous and devoid of crystalline structure.

The welder should from time to time make sample welds for himself, and, in order to prove their quality mechanically and physically, apply to them various simple tests, which will be outlined in a later chapter on The Testing and Strength of Welds.

Of the properties of the metals to be added, the first—and I think the most important—is that it should be as pure as possible, by which is meant freedom from all foreign matter detrimental to the mechanical properties of the line of the weld. In the welding of iron or steels the general weakness is the mechanical property of *elongation* in the welded part, and hence metal should be added which has the highest possible efficiency in elongation as its fundamental basis; for example, pure Swedish iron, made with wood charcoal, or electrolytic iron, which is even better.

To combat the ill-effects of the action of the resultant heat in a weld it is desirable to add to the welding material certain elements to counteract the various phenomena produced according to the material to be welded: such as silicon for cast iron, phosphorus or aluminium for iron or brass, copper or bronze, vanadium, nickel, or aluminium for steels.

However, it may be said here that such preparations should only be used when produced by those who are experts in the manufacture of welding materials, and possessing full and accurate knowledge of the technique of welding, and who exercise a control of their materials by a laboratory specialist.

CHAPTER III.

ELECTRIC WELDING PROCESSES.

GENERAL SURVEY.

ELECTRIC welding processes have been in use commercially since about 1886, when Prof. Elihu Thomson introduced his low-pressure resistance machine, invented about 1880.

During the last ten years several welding processes in which electrical energy is used have become well known, and, although unlike in apparatus and application, the fundamental principle of each system is to produce the heat for welding by means of resistance to an electric current.

The various types of apparatus have been perfected to such an extent in the last few years as regards efficiency and low operating costs as to displace largely the older methods of welding, and also to replace with great advantage melting, soldering, and brazing.

There are two main methods of applying electricity for welding purposes, viz., by internal resistance and by the arc, and each method is used in a number of ways for different classes of work.

The ramifications of these two main methods may be tabulated thus:

1. The La Grange Hoho process, resistance being formed in an electrolyte.
2. The Zerener electric blow-pipe method.
3. The Thomson process, sometimes called the incandescent process, or the contact process, as in the Thomson-Houston, Helsby, and Reiner welders. Under this heading come: Butt welding, spot welding, seam welding, angle welding, tyre welding, chain welding, wire welding.
4. The electro-percussive process.
5. The electric arc process, such as the Benardos system, the Slavianoff system, and their variants.

Although these several methods will be described, the author, in considering results, will devote himself mainly to those of which he has the most experience.

THE LA GRANGE HOHO PROCESS.

This process is generally known as the "Water-pail Forge." It was introduced from Belgium, but, as far as the author is aware, it has not a wide industrial application.

The work to be heated is fastened to the negative pole of the circuit and immersed in a bath of an electrolyte, such as "potassium carbonate" solution. The current when switched on flows from the positive pole through the solution, returning by way of the immersed metal pieces to the negative terminal. The solution is decomposed ; hydrogen in the form of a thin film is deposited on the metal pieces, which become red to white hot, and are protected from the solution by the hydrogen film. When the desired heat is reached, as told by the colour of the metal, the parts are taken out of the solution and welded together by hammering the joint on an anvil.

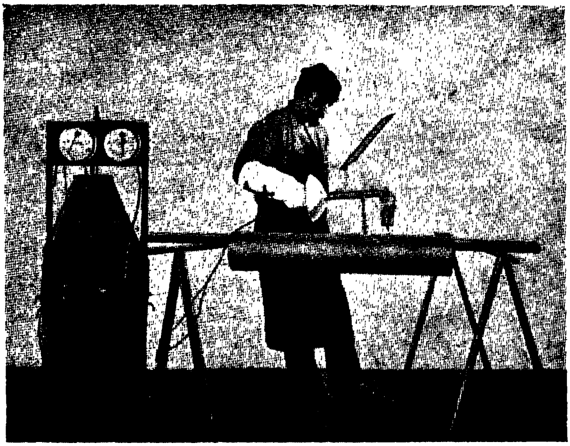


FIG. 1.—OPERATOR USING ZERENER BLOW-PIPE.

The advantage of this system is that the metals are thoroughly cleansed from all dirt and grease and oxide by the bath, while at the same time protected by the hydrogen film.

Against these are the disadvantages that the heat is not easily controlled, and the metals have to be worked in the air, where they soon oxidize.

THE ZERENER PROCESS.

This is an arc welding system, which was first used by Dr. Zerener in Berlin about twenty years ago.

Two carbon electrodes are employed in this system set at an angle, and the arc is blown down from the points on to the work by an electro-magnet. The carbons may be impregnated with oxide of iron, which is reduced to the metallic form, and the carbon vaporized by the action of the arc, thus preventing the carbonization of the work. With this type of arc welder the object to be welded need not be connected to the electric circuit.

Fig. 1 shows an operator using a Zerener type of welder. As can be seen by the illustration, the tools are fitted with shields to protect the hands, and the current passes through the insulated handle. An adjustable guide wheel steadies the tools. This process has only a limited field of application.

THE THOMSON PROCESS, OR RESISTANCE WELDING.

Electric resistance welding differs radically from all the other systems in forcing through the metals to be welded a current far in excess of their normal carrying capacity, and as the point of highest resistance is the joint between the parts to be welded, the maximum heat is generated in the very spot where it is required, and when the proper heat has been obtained the surfaces to be joined are pressed together to produce a perfect weld.

The apparatus necessary for resistance welding comprises :

1. A source of alternating current.
2. A step-down transformer (an integral part of the welder).
3. Apparatus for regulating the current, and for automatically cutting off the current as soon as the welding heat is attained.
4. Clamps for holding the parts to be welded and to transmit the current to them.

The latter three items are usually embodied in the welding machine as one unit.

This method of welding affords a number of decided advantages. The most important of these may be summarized as follows:

1. The metal is heated from the inside. When, therefore, the operator sees that the outer surfaces are at the desired heat, he can be perfectly certain that the metal is at the proper temperature right through.

2. There are no gases of combustion and no oxidation; hence these causes of faulty welding are eliminated.

3. The metal becomes one homogeneous mass free from porosity.

4. The work is easy, rapid, and efficient, and the temperature can be under proper control. Perfect supervision of the work is possible, and hence repeat work can be of uniform quality.

5. The clamps hold the work in perfect alinement, and furnish pressure to squeeze the hot metal well together.

All these advantages lead to economy in time, in labour, and in material.

CHAPTER IV.

METHODS OF RESISTANCE WELDING.

I. SPOT WELDING.

A SPOT welding machine is a device wherewith two or more sheets of iron or steel, ranging in thickness from 0.015 in. or 28 S.W.G. to 0.5 in. or 710 S.W.G., can be electrically welded together in such a manner that the mechanical effect of the welding is equivalent to riveting.

A series of small welds at regular intervals is made, each in the form of a small circular spot forming only a small percentage of the total area in contact, the diameter of the spots varying from about ⅛ in. to ½ in., according to the gauge of the plate.

Diagrams B, C, D and E in Fig. 2 illustrate various methods and types of electrodes for spot welding.

A marked feature of a spot weld is a slight depression on both sides of the weld (diagram F, Fig. 3), caused by the mechanical pressure of the electrode on the heated metal. This depression, however, can be avoided either on one side or the two sides of the weld; on the one side by using an electrode with a flat nose, which covers a much larger area than the other electrode; or on both sides by placing discs of iron or steel on the part to be welded, and releasing the pressure of the electrodes when the discs are level with the surface of the plate. By using electrodes with counter-bored noses, as shown in diagram G, Fig. 3, a weld can be made in the form of a ring instead of a spot; thus, for instance, if mild steel discs are welded in this way to a plate they can afterwards be drilled out, leaving a boss or collar round the hole intimately welded to and strengthening the plate, as shown by diagram G, Fig. 3.

A great variety of industrial work is now carried out with automatic or semi-automatic spot welding machines. The underlying principle is the same in all types of machines,

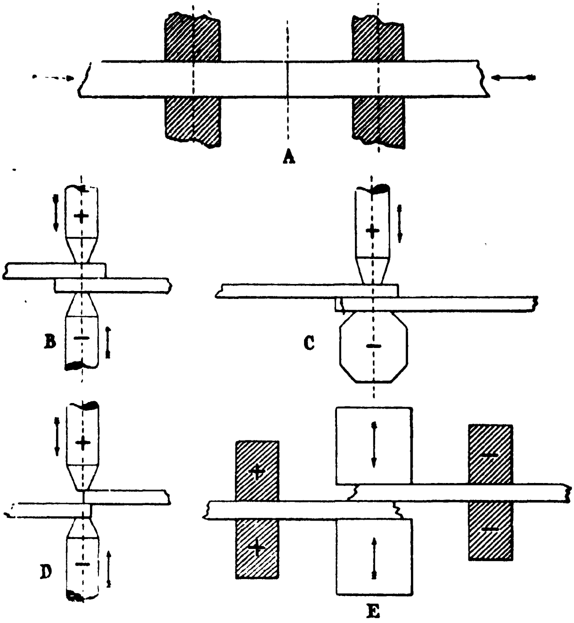


FIG. 2.—TYPES OF ELECTRODES FOR SPOT WELDING.

different makes only differing in detail mechanical arrangements. Descriptions of a few standard makes will give a very fair idea of the theory of spot welding, together with an insight of what can be achieved by their employment in modern practice.

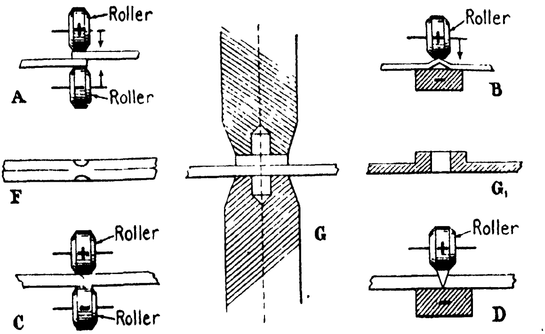


FIG. 3.—TYPES OF ELECTRODES FOR SEAM WELDING.

Spot welding machines are now manufactured in various standard sizes, each capable of dealing with up to a maximum thickness in material; which maximum is usually quoted as "added" or "aggregate thickness." From 0.125 in. to 0.75 in. can thus be welded, requiring a current consumption of 1 unit per 1,000 welds in thin material to 0.45 unit per weld in the thickest material.

The operation of the welders is almost the same in all sizes of machines. The work is placed between the electrodes and the pedal depressed; this closes the electrodes and also the current switch, causing the metal between the electrodes to heat up. When the metal has been sufficiently heated, the pedal is further depressed; this opens the electrical circuit, cutting off the current, while at the same time it compresses the heated metal, thus completing a weld. The article which is being welded is then moved along until the next required point of weld comes over the fixed electrode, and the cycle of operations is repeated.

Each machine is usually fitted with a multiple-way plug box for controlling the current to suit the different thicknesses of metal which it may be required to weld. In all cases the electrodes are water cooled, which prevents undue wear.

Compared with riveted joints, spot welds do not tear or loosen, and, in fact, give a much higher degree of strength at the joint. The electrodes generally have a tendency to leave a distinct depression and to cause a burn, as it were, between the plates, tending to keep them apart. This difficulty is circumvented by using an electrode on one side with a larger surface area, and inserting a small filling disc of metal on the other side prior to welding. A supplementary filling disc is particularly desirable, both to serve this purpose and also to concentrate heat at the point of welding when welding thick section material or attaching sheet metal to a solid part.

Fig. 4 illustrates one type of the renowned Prescot welders. This machine will weld strips of iron or mild steel to iron, or mild steel discs, up to 30 in. diameter; and was specially designed for attaching the distance pieces to dynamo and motor ventilating plates. The strips may be plain, rectangular pieces, or L, U, T, or other suitable section.

The welder is foot operated, and no skilled labour is required to work the machine. Depressing the pedal brings down the top electrode into contact and switches on the current. Directly welding temperature is reached, additional pressure on the pedal cuts off the current, whilst still maintaining the pressure on the weld, thus avoiding all risk of the weld being torn apart whilst still hot.

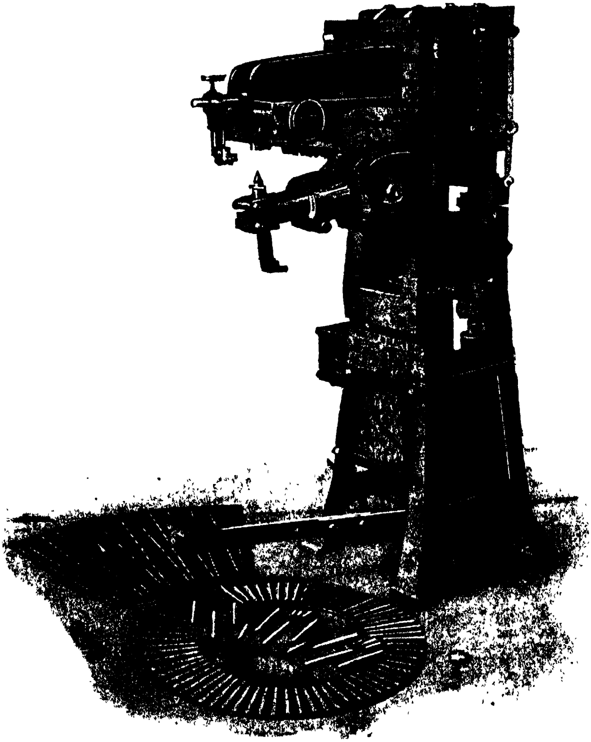


FIG. 4.—SPOT WELDING MACHINE.

The electrode tips are water-cooled and readily removable. A plug box provides four different heating speeds. A maximum of 10 kw. is absorbed by this machine.

A more powerful machine, designed for heavy work, is shown in Fig. 5. It will weld together iron or mild steel plates up to ⅝ in. thickness. The operation of this machine is exactly similar to that of Fig. 4. Varying lengths of stakes can be fitted to accommodate different work. A maximum of about 20 kw. is absorbed by this machine.

Many and varying types of welders are designed for continuous spot welding. Fig. 6A is an example of a power-driven welder for continuous spot welding of iron or mild steel plates of an aggregate thickness of $\frac{8}{16}$ in. This machine is fitted with an oscillating top electrode which continues to make and break contact so long as the pedal remains depressed. A spot weld is made each time the electrodes

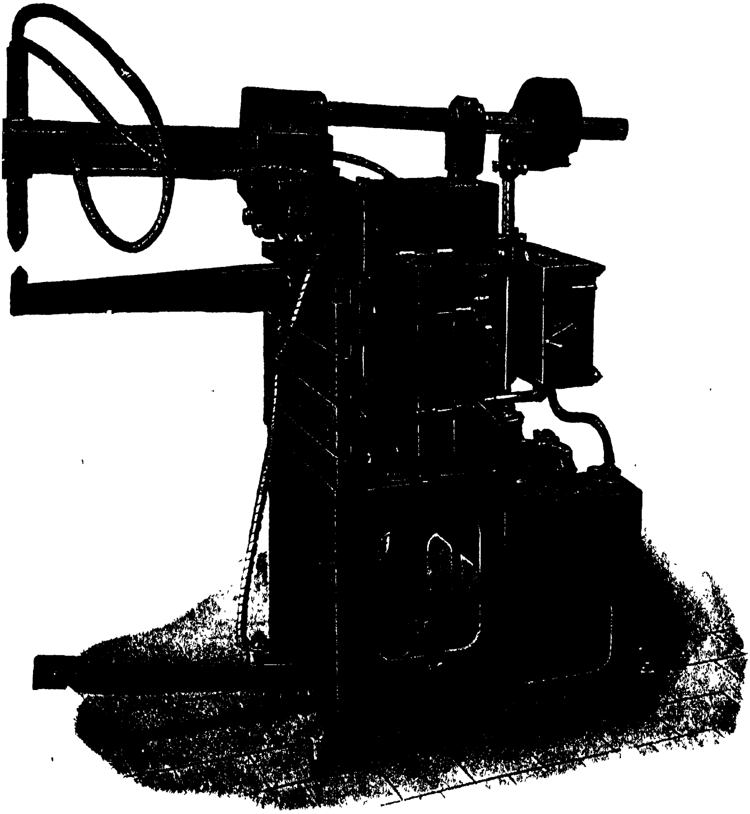


FIG. 5.—SPOT WELDING MACHINE FOR IRON OR STEEL PLATES UP TO $\frac{5}{8}$ IN. THICKNESS.

come into contact, the operator moving the work into position for the next weld whilst the electrodes are apart. The machine is used for welding the flat steel handles and bung necks to steel oil drums (Fig. 6B).

One of the decided and characteristic advantages of a spot welding machine is that galvanized iron can be quite successfully welded. The zinc coating volatilizes between the contact points, thus ensuring a true iron to iron weld, and, moreover, the protective coating in the immediate vicinity is not in any way affected or disturbed.

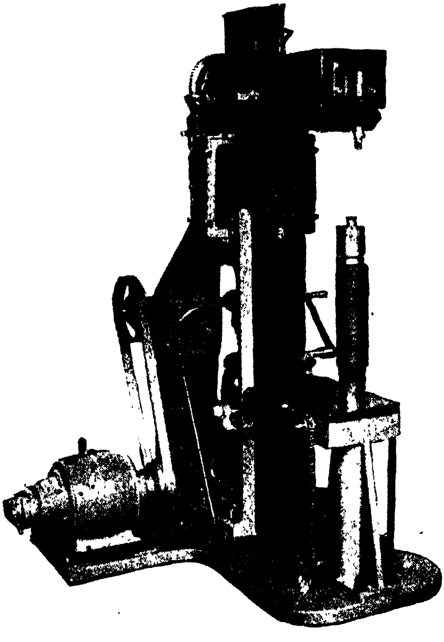


FIG. 6A.—SPOT WELDING MACHINE FOR WELDING CYLINDER ENDS, ETC.

However, the surfaces to be welded must be perfectly clean, as there is no action in the nature of the upsetting in a butt weld, which displaces dirt or oxide from the surface of the weld. Foreign matter intervening between the contact surfaces presents abnormal resistance, which, when broken down, causes a heavy rush of current, burning the work and electrodes.

Sheet metal corrugated in various forms can be easily welded to like sheets, or to flat sheets, which method may be used to build double sheet air-casings for stoves, metal pulleys, and generally many parts requiring sheets in close contact or a short distance apart. Such work can be effected rapidly, economically, and very efficiently.

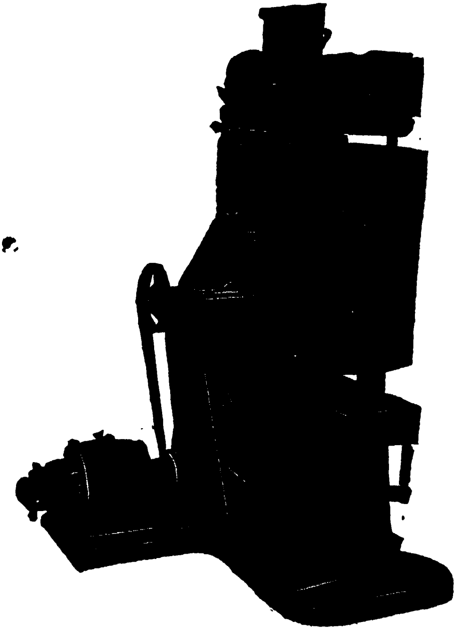


FIG. 6B.—DRUM IN POSITION FOR WELDING.

2. SEAM WELDING.

By this process two sheets of wrought-iron or steel are welded together along the edge by a continuous lap weld. The various methods adopted are illustrated in diagrams A, B, C and D, Fig. 3. The electrodes, it will be seen, consist of two rollers, or one roller and a fixed plate. To ensure successful welding it is very necessary that the plates, especially along the edge, should be free from rust. The bluish skin left after rolling the plates offers a high resistance to the flow of current, which can only be overcome by an increase in the electrical pressure, with the often disastrous result that when the scale is penetrated the sudden rush of current causes local overheating and consequent burning of the plate. Even if the plate is not burnt through, some of the scale will most probably adhere to, and become embedded in, the roller of the machine, thus increasing the already unfavourable conditions each time the scale on the roller comes into contact with the plate. Pickling, as a method for cleaning, is not advisable, as after this process the plates corrode very quickly. Rotary cleaners or sand blasting are the best methods for cleaning plates for seam welding.

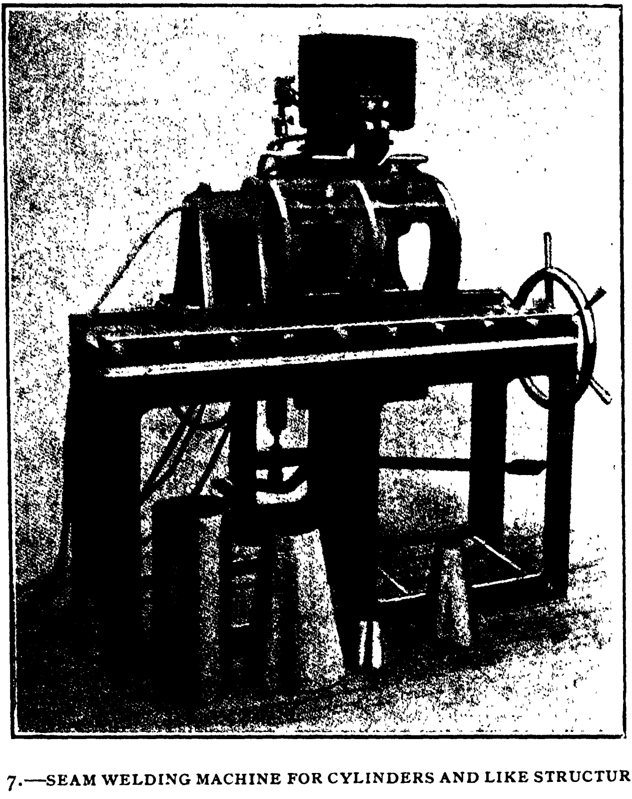


FIG. 7.—SEAM WELDING MACHINE FOR CYLINDERS AND LIKE STRUCTURES.

Plates varying in thickness from 0.25 mm. to about 3.5 mm. can be quite successfully seam welded at a rate of about two feet per minute with a current consumption of 0.04 to 0.4 units per foot of weld.

A Prescot Seam Welder is illustrated in Fig. 7. This machine is suitable for welding cylinders and like structures wrought-iron or steel up to 14 S.W.G. and 12½ in. diameter by 24 in. long. The articles to be welded are clamped on a conical mandrel by a specially shaped vice with four jaws. The mandrel is mounted on a slide and can be driven to and fro either by hand or by power under an adjustable roller electrode.

The illustration shows a machine equipped with a capstan wheel for driving the mandrel by hand: the mandrel and the roller are water-cooled and both journeys of the mandrel are used for welding. The roller is lifted off the work at the end of each journey by depressing a pedal which automatically opens the primary circuit of the welding transformer before the secondary circuit is broken, thus avoiding sparking and consequent damage to the weld.

The actual welding times on these machines vary from a fraction of a second for the thinnest to 40 seconds for the thickest material. The power consumption varies from as low as ¼ unit per thousand welds for very light work to 330 units per thousand for the heaviest material.

With very little alteration many standard machines can be adopted for special work, and in fact a very large variety of work is now most successfully accomplished with spot and seam welding machines which, before their introduction, necessitated expensive hand labour. As examples may be quoted: Fittings of all descriptions to enamelled hollow-ware, tanks, pulleys, sheet-iron tubes, spades, shovels, etc., automobile and bicycle parts, mudguards, expanded metal-wares, bonnets, fittings to chassis, etc., machinery parts, fuse parts, fan propellers, tin-wares, and a multitude of other useful applications.

3. BUTT WELDING.

The fundamental principle of Thomson's first welder, which was christened "The Nutcracker" welder (for the reason that it incorporated a clamp on each leg, and the welded parts were held where the nut would be), is still employed in the latest types of butt welders.

However, the latter are vastly more economical and efficacious, due mainly to mechanical improvements, such as parallel jaw slides, quicker and more efficient clamping, setting and swaging devices, and more complete and accurate control. The great commercial success of Thomson's system of butt welding really dates from the time when people realized that it could and should be designed and used as a specialized tool for manufacturing purposes, where strictly duplicate and repetition work could be of great advantage in reducing the manufacturing costs of many commodities by saving of time, cost of labour (unskilled instead of skilled now possible), saving of material and running costs.

The output of a single machine varies according to the size of the weld and the shape of the piece to be welded, and largely depends upon the operator, although skilled labour or high-priced labour is not necessarily required. Average intelligence and assiduity lead to perfectly satisfactory results from the modern welding machines.

From heavy work, or that requiring careful adjustment of the pieces in the clamps, to light work, or that which can be easily and rapidly handled, there is a very wide range. In some cases not more than 250 to 300 welds can be made in a day of ten hours, whilst on the entirely automatic type of machine as many as 8,000 welds are possible in that time.

To obtain the best results the surfaces in contact with each other and with the clamps should be clean and free from rust and scale, and touch each other as near the centre or core as possible.

The process is especially applicable to the butt welding of metals, having the same, or nearly the same, cross-section at the point of the weld. A limited difference can be corrected by giving the larger section more projection from the clamp ; but when the difference is very great the larger section should be reduced to that of the smaller for about a quarter of an inch from the point of the weld ; or in some cases the larger section may be heated first. These eventualities will be enlarged upon later in this article.

When the pieces are united, the pressure which forces the softened ends together makes a ridge or swelling round the welded joint. This surplus material can be removed if necessary by releasing the article from the welding clamps, which

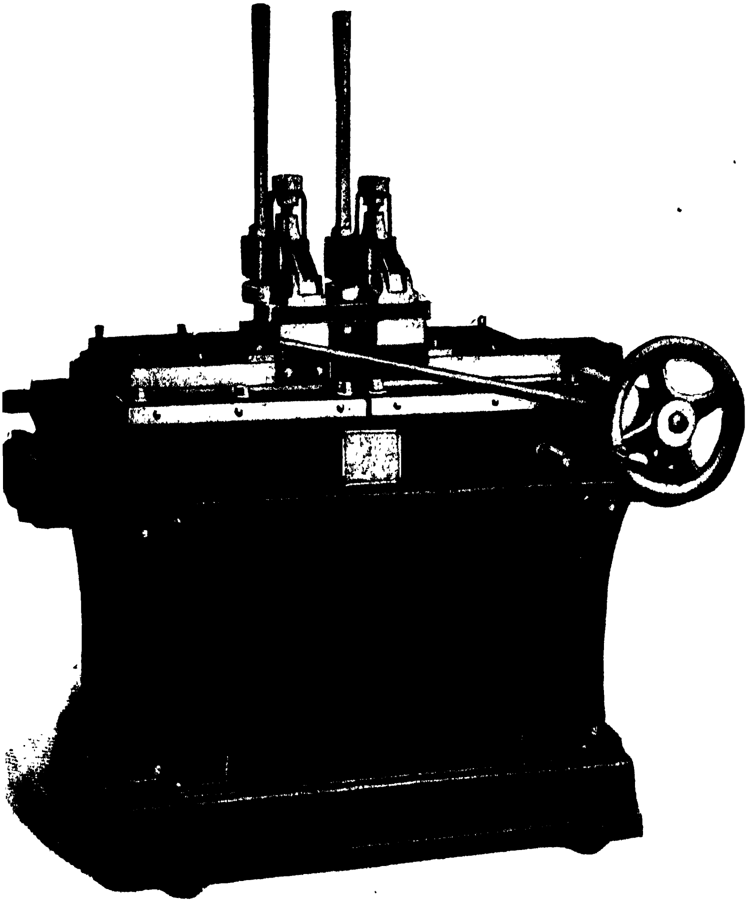


FIG. 8.—BUTT WELDING MACHINE FOR MODERATELY HEAVY WORK.

can be accomplished instantly, and placing the section at the welding heat under a power press or hammer with a suitable die ; it may also be treated on an anvil.

A very excellent machine, shown in Fig. 8, designed for moderately heavy work up to 2 in. diameter iron tubes, 1½ in. diameter iron rods, small tyres up to 2½ in. × ½ in. section, taking 30 kw. at full load.

This welder is hand operated, the principal feature being the pressure device, which consists of a screw acting on the moving plate, operated by a ratchet and pawl through a long hand lever. A hand wheel mounted on the ratchet wheel enables the plate to be drawn back rapidly for the next weld.

CLAMPING.

The arrangement of the clamping jaws is an important matter in butt welding, and worthy of careful study.

In the first place, they must be of sufficiently large mass in order that their resistance to the flow of current is negligible, thus economizing in power and wear and tear by prevention of high temperature except in the weld where it is required. Secondly, they must be of adequate mass and shape to firmly grip the parts to be welded, in order to keep the work cool and to localize the heat strictly at the line of weld. On the other hand, different metals require somewhat different treatment. Steel, pure copper, and like metals should be handled with care. They must be heated quickly, but if overheated they will lose their structure ; pressure at the joint and hammering or working while cooling strengthens the weld and prevents crystallization.

When metals of unequal conductivity are welded together the clamps are set according to the respective conductivities of the metals. Thus, for copper and iron, the iron clamp would be placed one diameter away from the end of the iron, and the copper clamp three diameters away from the end of the copper piece ; moreover, it is advisable to taper down the copper piece towards the joint.

High carbon steel can be welded up to about 0.8 per cent. carbon, but the metal should be locally annealed.

When welding low carbon steel on to high carbon steel, in order to secure the correct degree of heating and the time period of.upset, the former should project about two or three times as far as the latter.

The problem of correct clamping is even more important when other than simple end-to-end welding of round to flat stock has to be performed. For instance, the making up of angle pieces, tee pieces, and channel pieces, which can be quite satisfactorily and cheaply performed by butt welding, requires some special arrangements of clamps or dies. Very often it is advisable to employ auxiliary heating to allow for the greater mass of conductivity of one of the pieces.

One simple way of overcoming the difficulty is to employ three jaws, clamping the larger mass between two and passing current through to pre-heat same, then completing the weld by passing current between the pre-heated part and its component part held in the third jaw.

When manufacturing articles in large numbers the best procedure, before commencing the repetition work, is to set up two pieces having as far as possible correct relative and actual projections, known from previous or accumulated experience, and then to make a trial weld, carefully noting the time taken to attain to welding heat, or pre-heating heat or both, uniformity of heat, upset, &c. ; then adjust locking stops, upsetting springs, or other controls. Records of these settings should be taken, and charts can be drawn up for future guidance and to save time in finding adjustments for various classes of work.

Volumes of hints could be written upon the adaptability of various classes of machines to scores of industrial processes. However, if from these brief notes it is thought that possibly some particular phase of a manufacturing process could be more efficiently and cheaply performed with the assistance of an electric welding machine, the leading makers are always open to give advice as to the best types of machines and of ways and means of setting up the work. Their wide and varied experience will be found to be of considerable advantage.

CHAIN WELDING.

Probably the heaviest application of electric resistance welding is the welding of chain-links. Chains, heavy and light, can now be built up and finished completely from a coil of wire by means of automatic chain bending and chain welding machines. Links can be successfully built up and welded from a coil of wire up to $\frac{5}{8}$ in. in diameter. The following descriptions and illustrations were kindly supplied by the

British Insulated and Helsby Cable Company, who manufactured the famous Prescot welders.

The Bending Machine.—The coil of wire is first fed into a machine (Fig. 9), where it is cut off and automatically moulded into the required links, which are then fed into the welder, where they are joined up and welded and swaged, and passed out as a continuous chain.

The machine shown in Fig. 9 is of medium size. The maximum diameter of wire with which it will deal is $\frac{5}{16}$ in., and it will turn out 40 to 50 links per minute, the power required to drive this machine being only 2 H.P. to 4 H.P. The machine is belt driven, and is fitted with fast and loose pulley. The control is by hand lever. This lever is situated at the front of the machine at the right hand, or driving, end. There is also a foot-operated lever, attached by a chain to the hand lever, which, when depressed, throws the belt on to the loose pulley, and brings into operation a brake acting on the flywheel. This enables the machine to be stopped almost instantly in case of emergency.

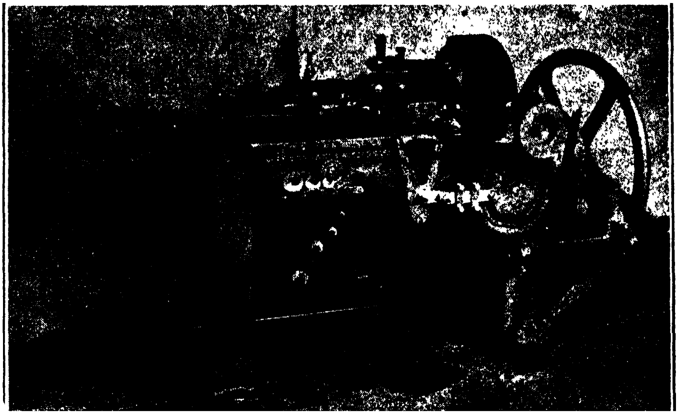


FIG. 9.—CHAIN BENDING AND LINK FORMING MACHINE.

Power is transmitted to the back shaft through a pair of double helical wheels. Mounted on the back shaft are three cams, the first of which is a triple-path cam, which operates all the tools forming the link. The centre path pushes forward the main slide. This slide carries a parting off tool and two bending tools, which form the link into a U shape from the back of the mandrel. The two side paths operate the levers carrying the tucking tools which close the link at the front of the mandrel.

The second cam on the back shaft operates the gripping lever, which holds the wire while it is being cut off. The length of the path of this cam can be varied. The adjustment for gripping different diameters of wire is made by a screw at the gripping end of the lever.

The third cam operates the feed. This cam is made adjustable, so that the length of feed may be regulated to suit any size of link within the range of the machine. From this cam the feet slide is operated through a bell crank-lever. The feeding end of this lever is fitted with a device which grips the wire on the feed stroke of the slide, and automatically releases it when the end of the stroke is reached. This gripping arrangement is fitted with a small cam which enables it to be thrown out of action at any time. The main use of this small cam, however, is to allow the machine to be started up, and the motions to be put into operation before actually starting to make chain. The cam is fitted with a lever for finger-and-thumb operation, and should be put into action when the slide is on the back stroke.

Running from back to front of the machine on the right hand is a shaft driven from the backshaft through a pair of bevel gears. Mounted on this shaft are two cams and a spur pinion ; the first cam operates the levers which raise and lower the top mandrel. This operation allows the formed link to be taken out by the fingers. The second cam is responsible for the in-and-out motion of the lacing spindle.

The pinion drives a spur wheel in the face of which is sunk a cam path. From this path motion is given to a quadrant which drives the lacing spindle in a semi-rotary manner. The semi-rotary movement is carried out in two stages each of 90 degrees. The stroke of the lacing spindle is adjustable.

The mandrel is made in two parts, upper and lower ; the lower part is stationary, acting only as a stop and stiffening block for the upper mandrel, round the bottom end of which the link is bent. The groove down the front of the mandrel is for the convenience of lacing.

An adjustable cutting die is fitted, so that the wire may be parted off clean.

On the extreme left of the machine is a straightening device consisting of eight adjustable rollers, four in the vertical plane followed by four in the horizontal plane. The rollers should be adjusted so that they make the wire reasonably straight and no more.

A safety arrangement is fitted on each machine at the driving end of the backshaft. This consists of four holes drilled through a special flange fitted to the end of the shaft and into the boss of the double-helical wheel. Four pins are supplied to fit these holes, but the number of pins used varies of course with the diameter of wire and size of link being made in the machine.

Operation of the Bending Machine.—The first two or three feet of the coil of wire should be straightened by hand, then, after slackening off the straightening rollers, the end of the wire must be threaded between the rollers through the gripping device on the feed slide and through the cutting die until the end is about ½ in. through on the mandrel side.

The straightening device is then adjusted, and the flywheel turned round until the shearing tool cuts off the projecting ½ in. of wire.

After adjusting the feed grip, main grip, length of feed and stroke of lacing spindle to suit the wire and link, the machine is ready for work.

First, the belt is thrown over on to the fast pulley and the feed slide is on the back stroke, the small cam is slipped over, thus bringing the feed grip into action. The machine does the rest, and its cycle of operations is as follows:

On the forward stroke of the feed slide the wire is pulled through the straightening rollers, and the end is fed behind the mandrel. As the slide reaches the end of the feed stroke the main grip comes down and holds the wire down on an anvil. While this is taking place the back slide is moving forward, and as soon as the wire is gripped the shearing tool cuts off the length for the link. This piece of wire is caught by the back bending tools and bent U-shape round the mandrel. Next, the tucking tools come into operation, and bend the ends of the U towards each other, thus completing the link. The lacing spindle now moves forward, and the fingers close on the completed link. As soon as the link is held by the lacing fingers, the top mandrel rises to allow it to be withdrawn. When the link is clear the mandrel drops down, and the wire is fed behind for the next link. Meanwhile the lacing spindle makes a quarter of a turn, thus changing the position of the first link from the horizontal to the vertical plane, and then moves forward again to enable the fingers to place the link in the groove in the mandrel. When the second link is formed it is threaded into the first link. The fingers then retire and are again turned through an angle of 90 deg. to the horizontal plane ready to take the second link.

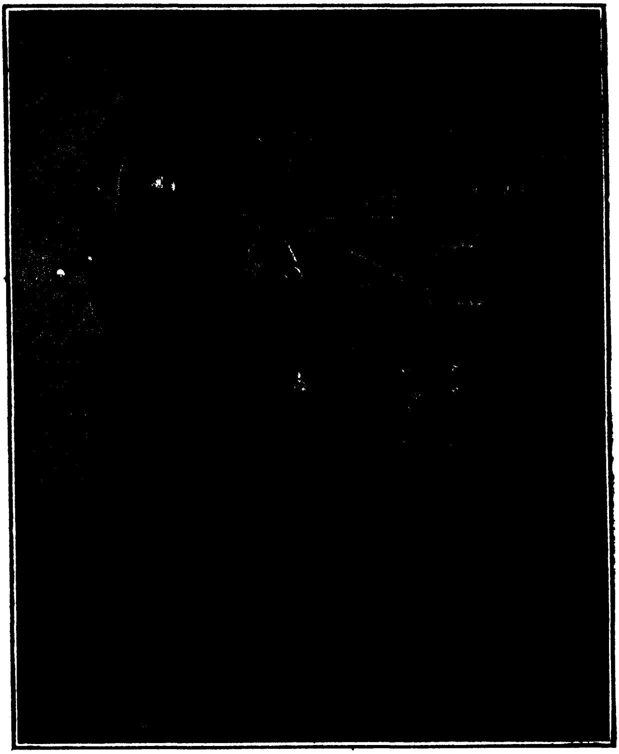


FIG. 10.—CHAIN WELDING MACHINE.

The motions of the lacing spindle are so arranged that the joint on every second link is on the same side, so that the chain when being welded has only to pass through the welder twice, and thus the cycle of operations is complete.

The Welder.—The assembled chain is next fed into the welding machine (Fig. 10), from which it is turned out a perfectly finished and uniform article. In this machine, which corresponds in size to the bending machine described above, from ten to eighteen links can be welded per minute, with a power consumption of about 2 H.P.

The machine consists of a cast-iron stand, on which is mounted a single-phase transformer and all the necessary working parts.

Mechanical power is supplied by a belt-drive on to a fly-wheel pulley. Spur teeth, cut on the inner side of the fly-wheel rim, drive a pinion and half clutch, which runs loose on the end of the cam shaft. The other half of the coupling slides along the cam shaft, and is thrown in mesh by a hand-operated lever on the left-hand side of the machine. All the cams are mounted on one shaft.

The electrodes are clamped in position on the front of the secondary casting.

The transformer is pivoted, and is tilted forward by a cam to bring the electrodes into contact with the link. A spring brings the transformer back after heating. Each of the upsetting tools is operated by a separate two-step cam. The first step closes the ends of the link to make contact, and the second upsets the weld. The upsetting tools are opened again by springs. The tools are provided with screw adjustment. The swaging tools are closed by cams and opened by a spring. Screw adjustments is provided to the tools.

The trimming tool, for cutting off the fins left on the link after swaging, is operated through a bell crank lever from a cam.

At the extreme right of the machine is the feed cam which acts upon a lever. At the feeding end of this lever is a pawl, which engages the links of the chain on the feed stroke and slides over them on the return stroke. The length of the feed is adjusted in the cam.

When being welded, the chain rests upon an adjustable saddle guide.

At the back of the machine is fitted a cam operated automatic switch. A main switch and fuse box is fitted at the left-hand side of the machine.

For regulating the heating speed at the weld a five-speed plug is provided at the back of the transformer.

The front part of the secondary is fitted with four water nipples, so that a flow of cooling water may be passed through to prevent overheating.

Cooling water should be supplied through a half-inch diameter rubber hose. The first connexion should be between the supply tap and the bottom nipple on either side of the secondary, the second between the top nipple on the same side of the secondary to the bottom nipple on the opposite side of the secondary. From the remaining nipple at the top of the secondary a third length of hose should be connected to the return tank or drain.

Operation of the Welder.—First of all, the machine is adjusted to suit the chain to be welded, then the main switch is closed, the cooling water turned on, and the machine drive set in motion.

Next, the chain is placed in position on the saddle with the first link resting on the bridge. It will be found an advantage to thread a piece of wire through the first link, for the purpose of feeding, until a sufficient length of chain has been welded to reach the feed box.

The clutch lever is then pulled towards the centre of the machine, and then released. This will engage the clutch; then the upsetting tools will close the joint of the link, and the transformer will tilt forward. As soon as the electrodes make contact with the link, the automatic switch closes, the clutch automatically disengages itself and heating commences at the joint in the link.

When welding heat is reached the lever should be pulled over again. This will put the cam shaft in motion again. The full cycle of operations which takes place is as follows:

1. The automatic switch opens.
2. The weld is upset.
3. The transformer tilts back.
4. The weld is swaged, and the upsetting tools release the link.
5. The feed draws the next link in position.

6. The fins are trimmed off the link, which enters the trimming box.
7. The upsetting tools close the joint in the new link.
8. The transformer tilts forward, and causes the electrodes to make contact at each side of the joint.
9. The automatic switch closes and heating commences.
10. The clutch is automatically thrown out.

If either electrodes fails to make contact with the links it should be adjusted by means of the screw provided for the purpose at its top end.

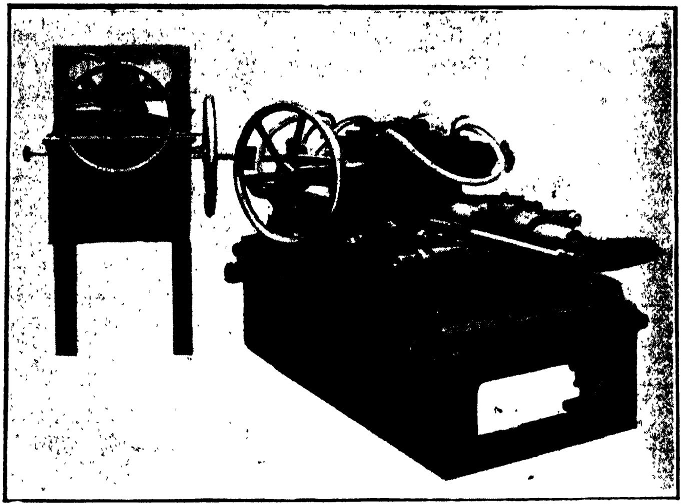


FIG. 11.—60 KW. MACHINE FOR TYRE AND HEAVY BUTT WELDING.

TYRE AND HEAVY MACHINE WELDING.

A large variety of heavy iron and steel work can be very successfully electrically welded by the Thomson or resistance method of machine welding, thus saving very considerably in time, in labour, and in materials.

In Fig. 11 is shown a 60 kw. welder fitted with clamps designed for holding a large variety of different forms of work, including straight and curved pieces, and suitable for welding in corners and other difficult places, in addition to ordinary straightforward butt welding. This form of machine has been largely adopted by wheelwrights for welding tyres of flat and channel section, and also by railway companies for repairing iron work of rolling stock. By welding on new rods to existing forgings very considerable economies are effected, while for welding tyres there is no process in existence equal to the electric butt method in speed, quality of weld, or cost of welding. In this machine the pressure device consists of a self-contained hydraulic jack operated by a long handle in front of the welder, giving a pressure of twelve tons on the weld. A heavy pressure applied to the weld while cooling greatly improves its strength and ductility.

The metal platings on which the clamping device is mounted are adjusted to get the required opening between the clamps, and the distance between the sliding jaws is adjusted by the small hand-wheels. The pieces to be welded are then inserted, and tightly gripped by operating the large hand-wheels, and lightly pressed together by the hydraulic jack. The circuit is closed by an external switch, and when the pieces are at a welding temperature the circuit is opened and the pressure is increased to force the ends together, upsetting the metal at the joint. The jaws are opened by the large hand-wheels releasing the welded piece, which can be placed hot under a hammer or press or the burr can be ground off cold. The contacts are water-cooled.

A heavy machine (Fig. 12) shows another tyre welding machine. The tyres are put in the vertical position, and are gripped by the hydraulically operated jaws. The latter feature is a great time saver, as the stock is gripped or released instantaneously with a further advantage that the weld reaches the anvil much hotter than would otherwise be possible.

The machine is suitable for welding tyres 20 in. in diameter and upwards, and of a sectional area up to 12 sq. in.

WIRE WELDING.

Wire welders are made in different sizes to weld from 0.024 in. diameter wire up to 1 sq. in. section. These machines are mostly fitted with automatic or semi-automatic upsetting and current-control gear. The parts to be welded are clamped between the jaws of the welder and the ends held together under spring pressure.

The current is switched on, which causes the metal to heat up where the weld has to be made. When the temperature is high enough, the ends are forced together by means of the spring, and the current is automatically switched off.

This type of welder is chiefly used for joining wires together, for redrawing, or for joining several lengths of rod together.

Fig. 13 illustrates a machine for welding steel wires up to ¼ in. diameter. The welder is fitted with auto-swaging and trimming attachments.

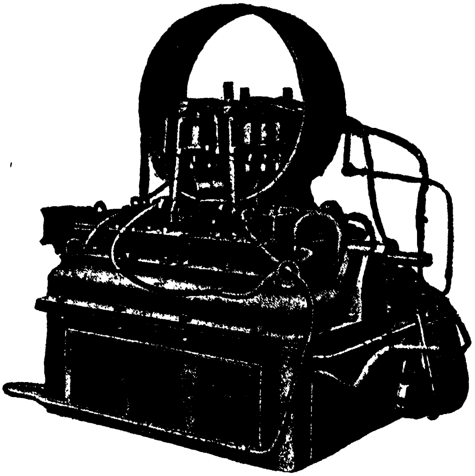


FIG. 12.—HYDRAULIC BUTT WELDER FOR HEAVY STEEL TYRES.

Fig. 14 shows a small hand automatic welder for steel and copper wires. In welding high carbon steel and copper the range of welding temperature is so limited that the weld must be made more rapidly than is possible by hand, and therefore the operation must be automatic or the metal will be burnt. This is accomplished by arranging for continuous mechanical pressure to be applied to the moving clamp by means of a strong spring, the pressure of which can be adjusted to suit different gauges of wire. The amount of such pressure is indicated, and can be read off, and the spring reset at any time for a given material with the certainty of obtaining uniform and sound welds.

The primary current is controlled by an automatic switch, which is tripped when the clamp has advanced a predetermined distance. The switch is also adjustable, and the point of cutting off the current is indicated on a scale to allow of resetting in the same way as the pressure spring. A welder of this type can be operated by totally unskilled labour, the only work necessary for the operator being to clamp the

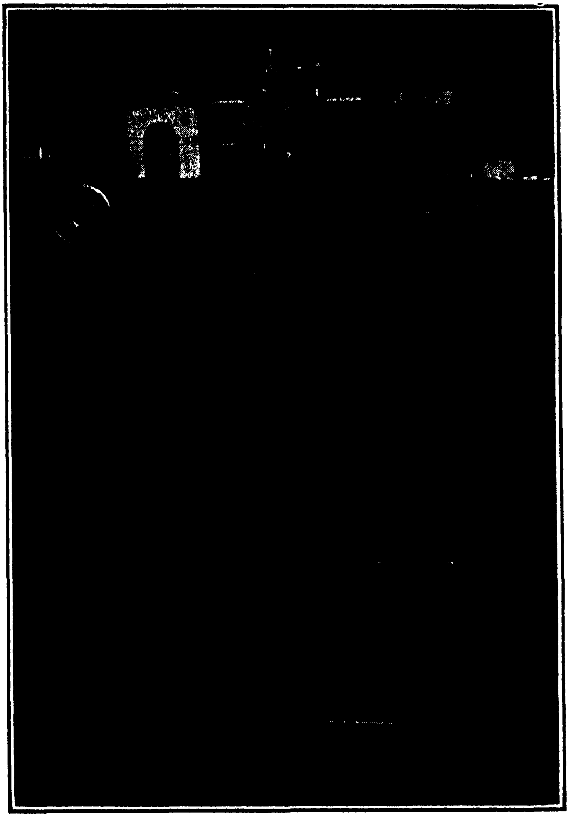


FIG. 13.—WELDER FOR STEEL WIRES UP TO ¼ IN. DIAM.

wires into position, press down the switch button, and remove the welded piece. These machines are largely used in cable factories, etc., for joining coils of wire into long lengths, both the copper conductors and the steel armouring wires being dealt with in this manner.

For the rapid production of wire rings, buckles, bag frames, and similar wire articles, a more completely automatic type of

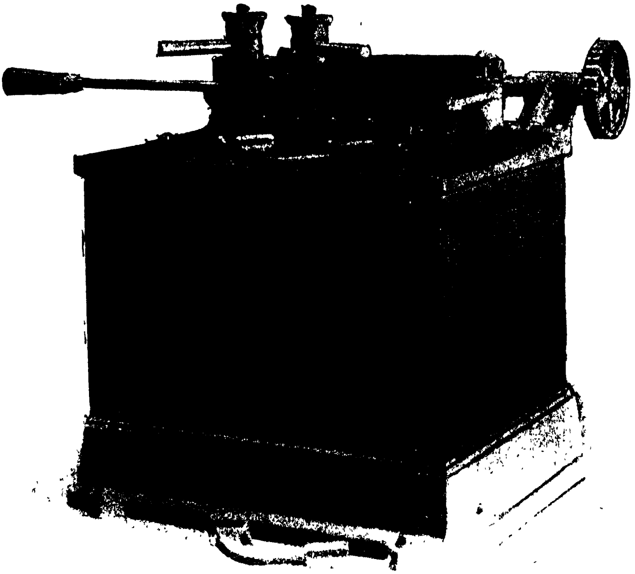


FIG. 14.—AUTOMATIC WIRE WELDER.

machine is used, as illustrated in Fig. 15. In this welder the clamps are opened and closed mechanically, and are continuously in motion, so that the operator has only to insert the unwelded article into the open jaws, when it is immediately gripped and welded automatically, the piece being removed and another inserted when next the clamps open. As many as 600 welds can be made per hour on this form of welder, which is extensively used for repetition work of the kind mentioned. The same principle is used in the manufacture of chains.

PREPARATION OF WORK.

The preparation of work preparatory to welding is generally very simple and obvious, one generally thinks ; yet, perhaps, for this very reason it is not always properly performed. It cannot too often be emphasized that work cannot be too clean for welding. In butt welding any reasonable amount of foreign matter is forced out of the weld automatically ; still, it is unreasonable deliberately to leave the surfaces to be joined in a dirty state. Perfect cleanliness in the parts to be welded, in the clamping jaws and gripping devices, prevents overheating, saves current, and eliminates risks of flaws and faulty welding.

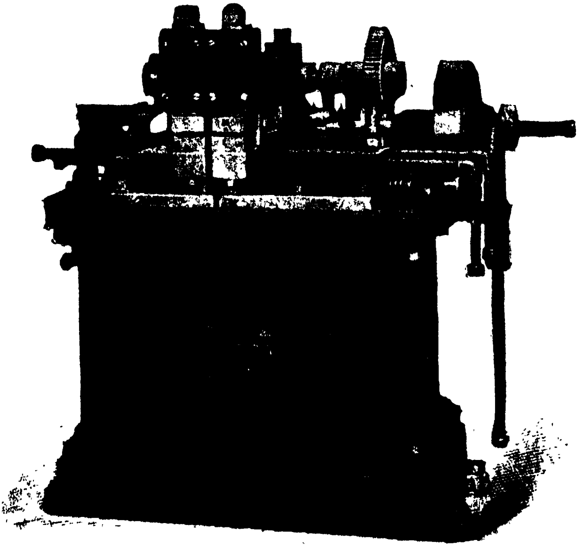


FIG. 15.—AUTOMATIC WELDER FOR MISCELLANEOUS WORK.

A sandblast, or grinding wheel, or pickling should be used to remove scale or oxide before welding is performed. A hot pickling bath of 1.50 volumes of sulphuric acid to water, followed by a thorough rinsing in milk of lime, affords a very satisfactory treatment for removing forging scale.

In butt welding operations it is always advisable to as far as possible arrange that the sections welded are equal. By a little forethought in the general design this is often possible. For instance, when welding bolt heads to round stock to save machining, it is the best practice to arrange the head with a stub turned down to the diameter of the bolt, the shank then being welded on to this stub. This example is typical of a multitude of repetition jobs, and such a method enhances the ease and reliability of welding, and the dressing up of the finished product is also facilitated.

After an electric butt weld is completed, it is often desirable to subject same to a further thermal or mechanical treatment. This after-treatment can usually best be given while the metal is still hot. It may be required to anneal, or harden, or to swage down any extruded metal formed during the process of welding. A butt weld may be annealed by increasing the jaw separation and passing a gradually decreasing current through the joint. Of course the value of this current will be of necessity considerably less than the welding current. Hardening may be similarly performed by heating to any degree electrically, and then quenching. Annealing is essential and important in the case of welded joints in high carbon steel and various alloy steels.

As the percentage of carbon increases, the difficulty of making a successful weld increases also. As high as five per cent. carbon steel can be electrically welded, but the danger is that it will harden in air to such an extent that any machinery or tooling of the joint will present considerable difficulty unless it is well annealed.

On the other hand, a weld in copper is soft, and consequently if the total welded mass has to be redrawn, the whole should be well annealed. Moreover, copper has to be raised to a much higher temperature than iron before it will weld, and it oxidizes very rapidly at this temperature. Also its melting point, unfortunately, is very near indeed to its welding point. Very accurate setting of the machine is therefore necessary. Brass and nickel have similar characteristics, with the additional disadvantage that the zinc and tin tend to volatilize before the copper constituent has come up to a welding heat. Aluminium, silver and other metals of the same group have a great affinity for oxygen at a welding temperature, and consequently the temperature should be kept as low as is possible consistent with obtaining a good weld. It is beneficial sometimes to interpose between the surfaces to be welded a flux plate to neutralize this objectional tendency to oxidation.

If required to prevent shortening the stock, a filling pellet or strip of metal can be forced in at the joint to allow for that displacement of metal at the moment of welding which is necessary for satisfactory union. The surplus metal can be automatically swaged down by means of pressure, or hammered or ground off.

REGULATION AND POWER CONSUMPTION.

Welding equipments are generally installed under expert supervision, and makers of electric welding machines can usually provide equipment to suit existing arrangements of current supply. Welders can be obtained for nearly all applications suitable for working on the usual standard voltages, and except in the case of very heavy machines can be operated on any one phase of a three-phase circuit. The regulation is now universally provided in the primary of the welding transformers. The form it takes varies according to the type of machine. Usually the secondary current is regulated by resistance in the primary circuit, by varying the primary turns, or by varying the field excitation of the generator, if a special generator is used, though this is not often the case, for if more than one welder is on the generator bus-bars, varying the excitation may suit one welder and upset the other.

Varying the primary turns, say, 75 per cent., 60 per cent., 50 per cent., and 25 per cent., by means of a plug switch, or some other convenient means, affords a coarse regulation which can be further improved by reactance. The circuit is opened in the primary circuit to avoid damage to switches, jaws, or the work, by interrupting the heavy secondary current directly. The current consumption in heavy welding may be reckoned in tens of thousands; however, the P.D. is very small, ranging from about ½ to 7 volts. Thus the energy expenditure is very small, and indeed it is found the cost of current consumed is small compared with the cost of labour, directly and indirectly. Moreover, the form and the shape of the work to be welded considerably modifies the energy consumption and the welding speed. For example, the current required to make a satisfactory weld in a ring is considerably in excess of that required to weld a straight bar of equal section.

Again, a weld can be effected with a certain current for a certain time, or with a less current over a longer period. However, it has been proved that there is one particular speed of welding which gives the best economical results. From the curves, Fig. 16, it will be seen that the power

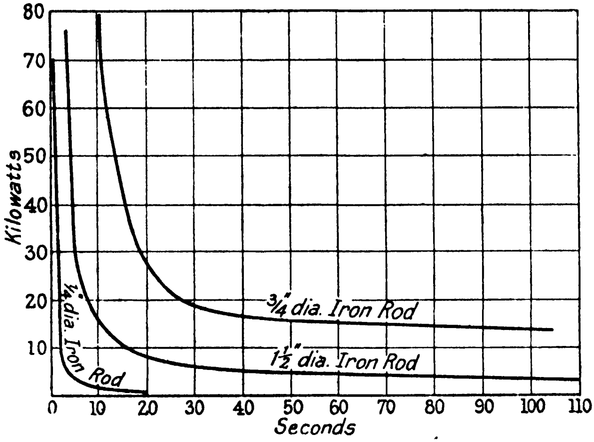


FIG. 16.—CURVES SHOWING RELATION BETWEEN KILOWATTS AND WELDING SPEED. PRESSURE OF UPSETTING SPRING CONSTANT.

required to speed up a weld rises abruptly after a limit in reduction of time of making a complete weld. Moreover, as has been already pointed out, the running cost is usually so small compared with the labour and standing charges that it would pay to reduce the times shown in the above curves to a value somewhere on the knee of the curve ; beyond this the capital cost and size of equipment increases beyond a practical limit.

If a welded bar fails either side of the weld, and not through the weld, it is usually a sure indication that the operation has been speeded up beyond an economical limit. The reason is that the heat has not had time to defuse backwards into the bar, with the consequence that there is a sudden line of demarcation at either side of the weld where the microstructure of the metal changes.

A welded rod should not (as is most commonly supposed) break outside the weld, unless of course the weld has been reinforced. The author has often seen test sheets of specimens of welding showing that the weld has stood firm, and the specimens fractured beyond the weld. This, although on the surface it appears to be highly satisfactory, is in reality a proof that the process of welding has reduced the tensile strength of the original stock locally.

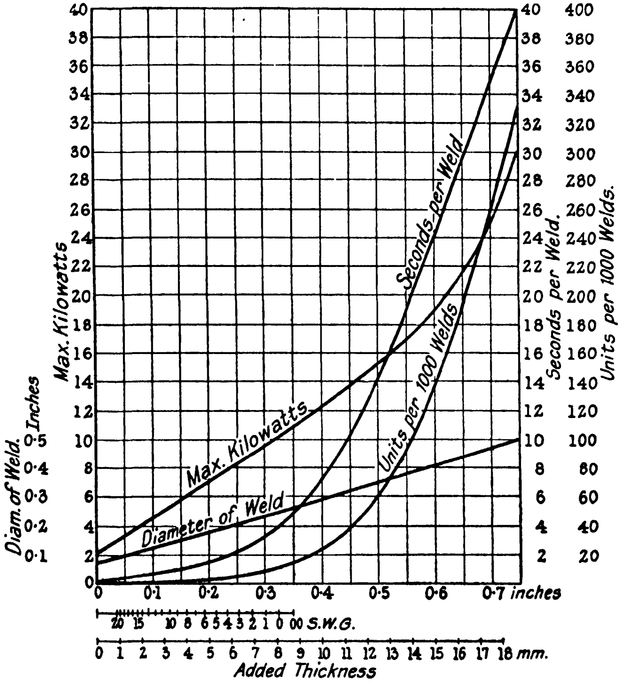


FIG. 17.—SPOT WELDING CURVES FOR EQUAL THICKNESS OF SAND-BLASTED M.S. PLATES.

In conclusion, it may be again stated that the fundamental characteristic of electric resistance welding is the use of very

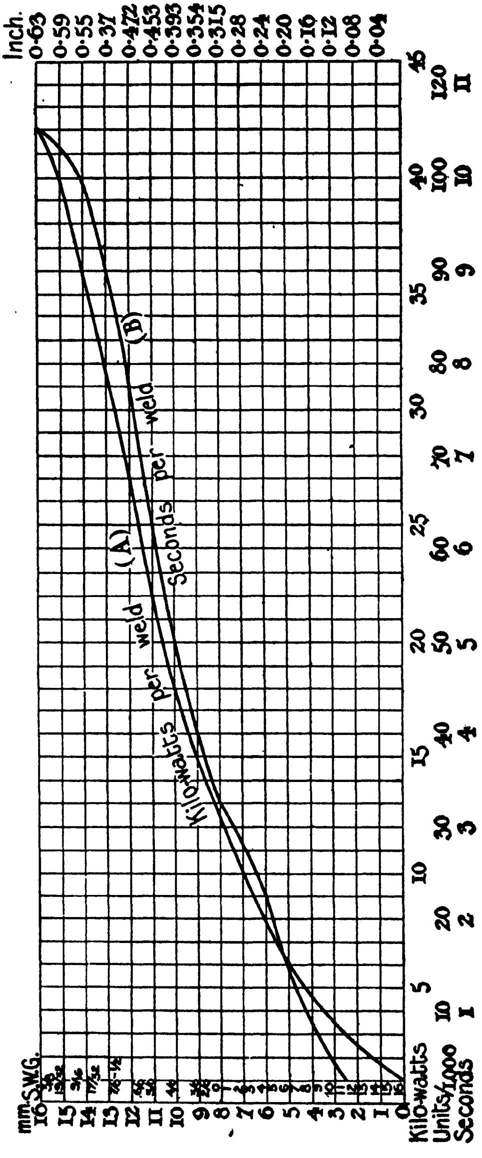


FIG. 18.—BUTT WELDING CURVES FOR COPPER. USED IN WELDING COPPER WIRE OR STRIP UP TO 5 SQ. IN. SECTION

heavy alternating currents, and its useful field of application is limited therefore to repetition work, where it reigns supreme by virtue of its simplicity, speed, reliability, and great economy.

The series of curves, Fig. 17, show the maximum current required, consumption per 10,000 welds, diameter of welds,

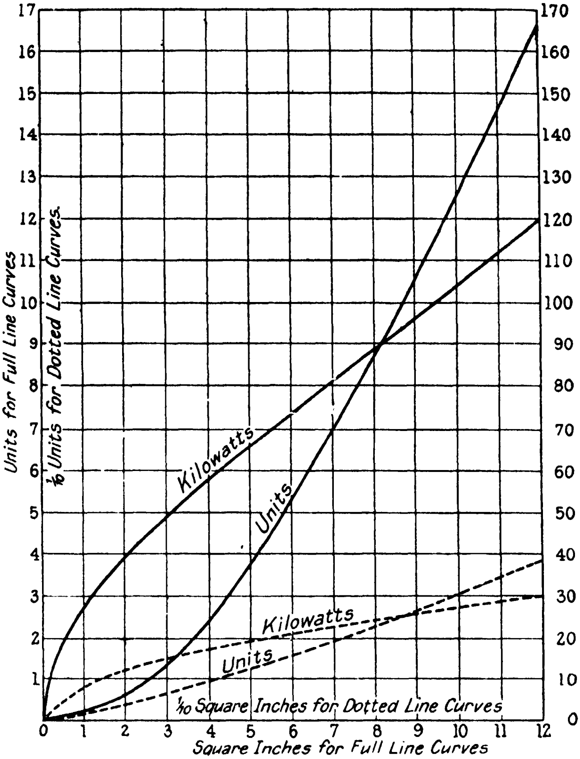


FIG. 19.—APPROXIMATE CURRENT CONSUMED PER SQUARE INCH OF IRON ON PRESCOTT WELDERS.

The curves represent the average from a great number of butt welds in round, square, and irregularly shaped bars.

and time taken to complete a weld in seconds on a spot-welding machine.

Figs. 18 and 19 also show similar curves for butt welding iron, mild steel, and copper, while Fig. 20 gives a series of curves for seam welding mild steel sheets.

These curves, kindly supplied by the British Insulated and Helsby Cable Company, are not perfectly accurate for every make or type of machine. However, they may be taken as fairly accurate guides for reference and for preliminary adjustments of a machine prior to setting it for any particular run of work.

It will thus be seen that the current consumption is very small compared with the quantity of welds made.

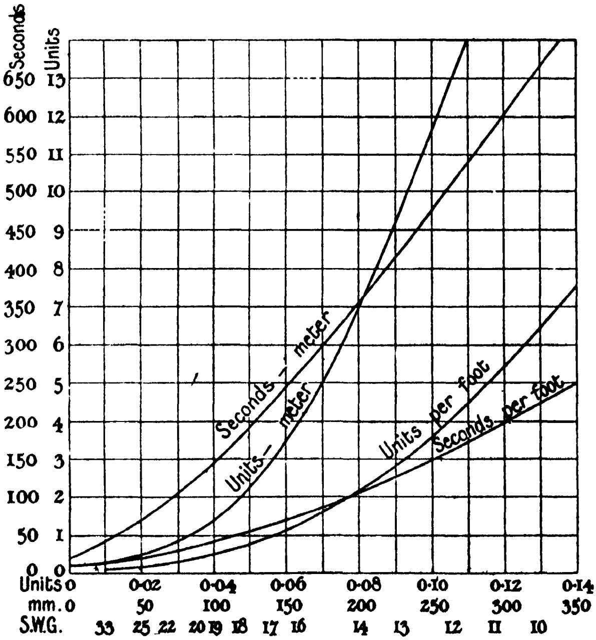


FIG. 20.—SEAM WELDING CURVES FOR IRON OR MILD STEEL.

In spot welding the consumption varies from one unit per thousand welds in thin material up to 0.44 unit per weld in the heaviest plate ¾ in. (added thickness).

Hoops and tyres from 1 in. to 10 in. in width can be welded at the rate of about 5 to 15 per hour. Five hundred to one thousand, and sometimes even more, spot welds can be made per hour, each weld being equivalent to one rivet

ELECTRO-PERCUSSIVE WELDING.

The latest process of welding, called " Electro-percussive Welding," is another method of employing the principle of heat developed by the passage of an electric current in overcoming a resistance. Up to the present time, however, comparatively little is known of its possibilities and adaptability. Nevertheless great hopes are centred round this new system of electric welding, and even in its early stage of development for very fine work and in range of metals that can be welded thereby it surpasses all other methods.

The system was discovered by Mr. W. Chub about ten or twelve years ago while experimenting with electrolytic condensers and rectifiers. He found that the wires could be welded to an aluminium plate by the spark from the condenser when the cells were discharged. Experiment further showed that different metals could be thus temporarily welded together. Mr. Chub was thus encouraged to try the effect of joining metal wires with a condenser discharge on a more ambitious scale. Careful theoretical consideration of what happened during these early tests led the experimenter to the belief that successful welding depended upon several variables, such as the capacity of the condenser, the voltage, inductance and resistance in circuit. The effect of the above variables were tried out in turn, and in a later welding apparatus designed in line with observations and results of these experiments, the effect of variation of velocity of impact, momentum and kinetic energy were proved.

Finally, a successful electro-percussive welding machine (Fig. 21) was evolved, much resembling a toy pile-driver, in which the " monkey " carries one of the pieces to be welded.

The principle involved is that of bringing two parts into contact at a high velocity and with a condenser discharge, occurring at the *instant* of such impact. The heating due to the resistance to the passing of the discharge through the joint is extremely local, and the explosive violence of the electrical discharge blows out any impurities from the joint, thus making it possible and practicable to make reliable joints between almost any dissimilar metals.

The depth of metal at the weld which is heated to any appreciable degree is probably about two to three-thousandths of an inch. The heating is extremely local, and a perfect contact and union is effected at the film of the weld, which explains why metals of totally different physical and chemical characteristics can be successfully joined together.

Fig. 22 is a diagram showing the connections of this method.

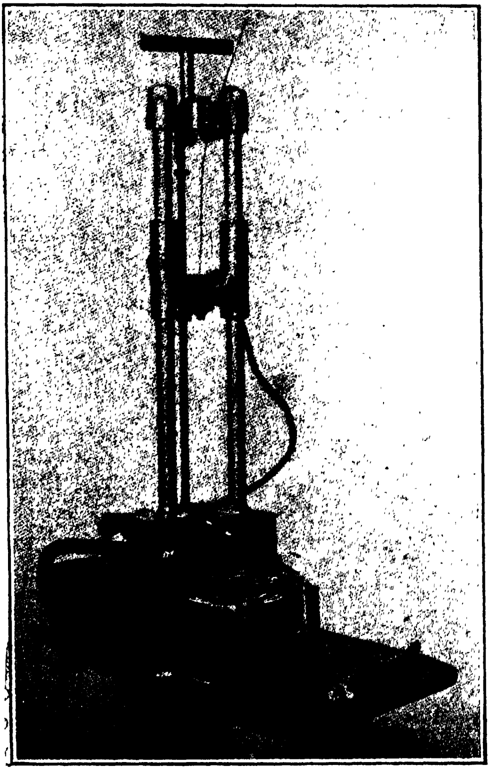


FIG. 21.—GRAVITATIONAL TYPE OF ELECTRO-PERCUSSIVE WELDING TOOL.

The circuit consists of a generator *G*, which charges an electrolytic condenser *C* through a high resistance *R*. The voltage across the charged condenser is adjusted by means of varying the resistances $R \phi R^1$, or by altering the field excitation or control of the generator.

The wires to be welded are gripped in the grips W, W^1 of the welding tool, which are connected to the terminals of the condenser through an inductance L. A spring switch S, which is normally held closed, is connected across the clips of the welder, so that their P.D. will be zero while the wires are being inserted or the finished weld removed.

The operation of welding is as follows : The two wires to be welded are fixed in the jaws of the machine, and their ends cut off as short as possible with suitable wire cutters. The switch S is opened, thus charging the condenser to its full voltage. The top moving jaw is then released, and the two ends of the wires brought into percussive engagement. The short-circuit current builds up at the instant of contact to such an extent that the ends of the wires are melted and the weld is intimately forged by the blow of the falling mass and the explosive discharge of the condenser.

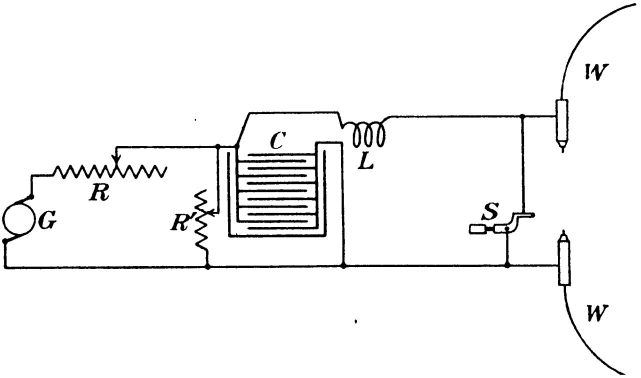


FIG. 22.—DIAGRAM OF ELECTRICAL CONNECTIONS FOR ELECTRO-PERCUSSIVE WELDING.

The strength of such a weld is found to be equal to that of the original wire.

At the moment of short-circuit, when the two masses come into percussive engagement, the heat developed is so extremely local, so intense and so sudden, that it is impossible for the factors which usually have to be contended against in arc welding, such as unequal expansion, unequal conductivity, melting point and difference in chemical properties, to have any effect on the weld or the total mass. Hence, any combination of metals can be quite successfully welded by this method.

Application.—Electro-percussive welding has already been used extensively for joining together aluminium wires, copper and aluminium wires, platinum and copper, platinum and nickel; also the welding of thermocuple wires. Moreover, many odd pieces and lengths of wire or strips of valuable metal can be saved by welding these lengths together as required.

Electro-percussive welding opens out a large field of welding, which up to the present was impossible; moreover, many possibilities of its application have not yet been tried.

In the jewellery trade it has already superseded the older arts for joining of platinum, etc., welding of sterling tips on table cutlery, welding pins on badges, brooches and numerous like applications.

In the electrical trades the system is now applied largely for the attachment of contact points of platinum, silver, tungsten, etc. The joining of copper to aluminium in field coil leads, or strand by strand in cable work, is of particular interest and importance to the electrical engineer and manufacturer.

DEVELOPMENTS AND POSSIBILITIES.

Electric welding can be regarded as a new industry, although this may come as a surprise to some of the old-time welders. Nevertheless, we are only now in this country and America taking up the matter seriously. Practice has preceded the scientific investigation, the field of future application, therefore, is full of interesting problems. The spot and seam welding of copper and other non-ferrous metals and their alloys has got to be made practicable and spot and seam welding machines built to weld heavy plating, such as ½ in. and up to 1¼ in. In America the application of spot welders in ship fabrication has lately received considerable attention and promises great encouragement. An experimental apparatus of large size was erected and put into operation, the results showing that no difficulty was encountered with ½ in. and ¾ in. plates. In fact, this experimental machine was successful in welding three thicknesses of 1 in. plate, a condition which far exceeds the requirements of merchant ship construction. This operation has its historical significance, in that this was the first time that any spot welding of this magnitude had been performed. The successful outcome of these experiments has led to the design and construction of large spot welders to be used in the fabrication of ship sections. The practical application of a large 5-ft. gap spot welder will be made at a demonstration of a 40 ft. section of a standard 9,600-ton ship to be built at the plant of the Federal Shipbuilding Company, Kearney, New Jersey. This is the largest portable spot welding ever built.

The tendency of developments in spot welding has already been slightly touched upon. In their nature as applicable to shipbuilding the advancement will naturally have to proceed towards means for accomplishing spot welding in very cramped locations. This makes an exceedingly difficult problem, as the power requirements are such as to preclude any very small device. In riveting, one-half of the apparatus is on one side of the work and the other half on the opposite side, and it is difficult to conceive of any method of spot welding that will admit of such an arrangement. In shipbuilding, it is quite probable that designs may be made that will permit of a large, or at least increased, amount of spot welding in the actual construction of the vessel. So far as the author is aware, no move has been made in this country up till now to develop very heavy seam or spot welding machines. The problems are not insurmountable, however, and the industrial research committees in this and other countries will, we hope, in the near future investigate and develop electric resistance welding in a thorough and scientific manner, and thus give to industry a further impetus and another labour-saving device to compensate for the lack of hand labour and the ever-increasing desire to speed up production.

CHAPTER V.

ARC WELDING SYSTEMS, EQUIPMENT AND MACHINERY.

ELECTRIC welding has, owing to its cleanliness and susceptibility to precise adjustment, been highly developed in modern practice, particularly, as we have seen, are these advantages obtained in resistance and spot welding.

Another problem, however, is introduced when it is required to repair existing structures by welding-up defects *in situ*. Obviously new material is required to make up for wastage from corrosion, or fill up various defects, or even to build up new parts to broken structures; hence, what is required is more in the nature of a depositing or brazing process.

The Benardos system employs a carbon or graphite electrode connected to the one pole of the source of supply, the article to be welded being connected to the other. The graphite rod which forms the negative electrode, varying in size from ¼ in. to 1½ in., depending on the amount of current required for the work in hand, is held in an insulated holder, and an arc is struck by bringing the end of the carbon pencil in contact with the work and quickly withdrawing it a few inches away from the metal. Figs. 23, 24, and 25 show a workman using this apparatus.

Direct current is required for this purpose and ranges from 100 to 800 amperes per circuit, depending on the nature of the work, the size of the piece and the material. Average work, however, requires from 200 to 500 amperes.

The best results with the Benardos system are obtained with current supplied at about 75 to 80 volts., but when this potential is obtained from a higher voltage circuit through resistance, instead of from a low-voltage generator, there is a great loss of energy, and moreover the quality of work is likely to be impaired.

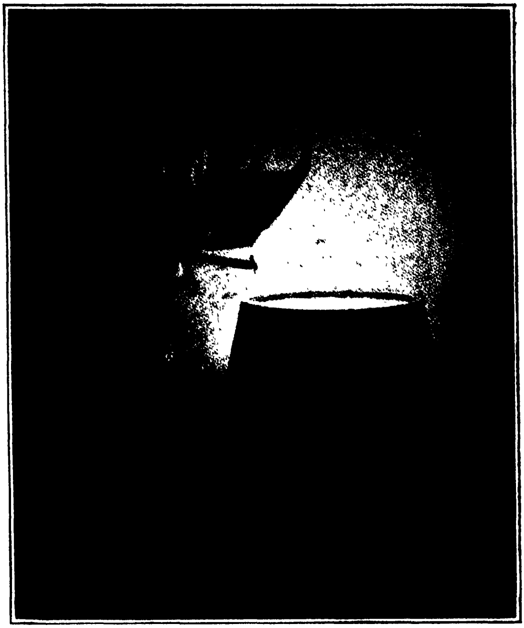


FIG. 23.—WELDING SEAM OF A BARREL, WITH GRAPHITE ELECTRODE.

FIG. 24.—WELDER USING METALLIC ELECTRODE.

The Slavianoff process is similar in principle to the Benardos system. The carbon electrode in the latter system being replaced by a metal electrode, which gradually melts and supplies the extra metal for filling in or for building up.

For heavy cutting, repair of defective castings, and for general welding work the Benardos system is usually the more adaptable and more economical. The Slavianoff process, on the other hand, is usually employed in general repair work, and on light and more delicate work, though as far as present practice goes the metal electrode system is not suitable for welding copper, brass, and copper alloys.

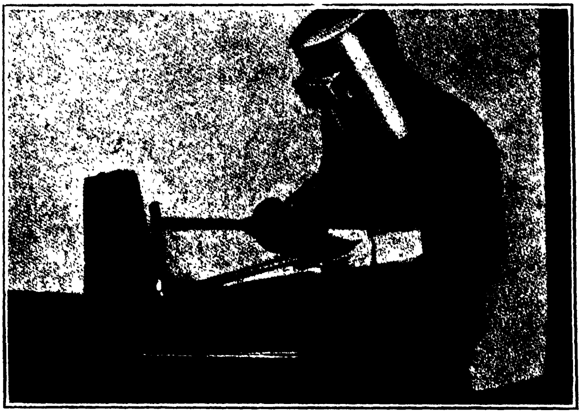


FIG. 25.—WELDER USING GRAPHITE ELECTRODE AND FILLING ROD.

It is impossible to draw any hard and fast rule as to when and where each process should be used. A well-designed installation allows for either or both systems to be in operation.

Under the heading of " Application " some typical classes of work for each process will afford some guide as to whether the Benardos or metal electrode system is the more applicable to a particular class of work.

The characteristics of the arcs in these two systems differ in many respects. In the Benardos system, average work requires from 200 to 500 amperes with a voltage drop across the arc of 30 to 50 volts. The arc is usually from 1½ in. to 6 in. long, but should be perfectly stable within these limits.

For very heavy work, currents as high as 800 to 1,500 amperes are used, but these cases are exceptional and have no bearing on average practice.

In the Slavianoff process the maximum current used approximates to the minimum current used in the former process. The range is from 10 to 250 amperes, though average work is performed with 50 to 175 amperes. The drop across the arc varies from 18 to 30 volts, while the length of the arc is very short, rarely exceeding $\frac{3}{16}$ in.

The metallic electrode system of electric welding has the great advantage over all other processes in that, owing to the peculiar action of the arc, the metal from the electrode is carried on to the work in a direct line, thus making it possible to work successfully overhead or on a vertical horizontal surface. Much discussion has taken place amongst various authorities in the past on the question of successful overhead welding, and many schemes have been devised by so-called experts to accomplish successful overhead welding, and, of course, each one has been claimed by its originators to be the only practical and efficient method.

One of these schemes consists of an electrode holder containing a coil, usually in shunt with the arc. It is claimed that the coil sets up a magnetic field in such a direction that the particles of molten metals from the electrode are directed to the weld, thus causing the filling metal to attach itself in particles to the article being welded. In practice this scheme, however, is found to possess no real or unreal advantages, neither does such a coil assist the welder in any way. In theory this arrangement is futile when it is borne in mind that the temperature of the electric arc is in the region of 3,500°C., and that iron becomes non-magnetic at a temperature approximately 750°C. The fallacy of this scheme is thus self-evident.

Another arrangement is that of coating the metal electrode with a non-combustible and non-conducting coating, which has the effect of causing the end of the metal electrode to melt in the form of a cup, thus supporting the molten metal while being distributed upon the weld.

Another theory put forward is the " Pinch effect." This pinching effect is caused by the magnetic field which surrounds any conductor carrying current and which tends to contract the material of the conductor. Of course, if the conductor is solid there is no pinching effect, but if the material is fluid, or semi-fluid, it causes the material to contract, or pinch. That this pinching does exist there is no doubt, but whether it has any influence in the operation of welding it is difficult to say. Moreover, it is claimed that a coating around the electrode is essential to successful vertical and overhead welding.

In the author's experience successful overhead welding is dependent on none of the above properties. The electrode need not necessarily be coated, though in practice generally the electrode is coated with a flux, the flux, however, performing another function entirely. Undoubtedly the test of a welder's skill is shown in the degree of his efficiency in welding on a vertical and overhead plain. The points which go to assist in successful overhead welding will be dealt with in a later chapter. *When work is performed by skilful operators, welding performed on a vertical or overhead surface is, in the author's experience, more successful even than welding on a horizontal surface.* The reason for this possibly is that impurities are more easily kept out of the weld, and usually a smaller surface is exposed to oxidation.

MACHINERY AND EQUIPMENT.

Although arc welding plant and equipment has received increasing attention in the past, there is still a very considerable scope for improvement in type of generating machinery and materials used in the weld.

Unfortunately, there are yet many authorities who hold diagonally opposite views as to which is and which is not the best system and best type of machinery, and therefore it is unwise in a general way to recommend too strongly one or other school of opinion. For encouragement, the author ventures to say that with each and every system herein described it is possible, under the directorship of a first-class instructor, to turn out good welding, and, indeed, an equipment which embodies the best characteristics from each system can be very flexible and complete with any known welding process of modern times.

The equipment of an arc welding installation comprises :

1. Suitable generating machinery for supplying current to the arc circuit.

2. Control gear, switch gear, and arc-regulating devices.
3. Electrode holders and electrodes.
4. Protective coverings for operator and the work.
5. Fire clay, ganister, carbon blocks, clamps, earthing devices, etc.
6. Fluxes and filling material.

GENERATING MACHINERY.

Although arc welding has been done, and can be done, from any medium voltage circuit, provided sufficient resistance or reactance is in series with the arc to cut down the current to the value required at the arc, it is now universally recognized that this method is extremely wasteful and inefficient.

Arc welding is best accomplished with direct current at 75–90 volts in the case of the Benardos system and 50–65 volts with the metallic electrode system. A low-voltage generator is therefore generally used to-day specially wound to give the right characteristics for arc welding, driven by an electric motor, petrol engine or steam engine. The generator should be of the commutating pole, compound-wound type, with separate shunt field excitation. When more than one arc circuit is to be run off the same generator, the compounding should be from 1¼–4 per cent. above level characteristic.

An arc welding load is extremely severe, and the very frequent overloads which have to be borne by the generator and prime mover necessitates most careful and robust design. Moreover, the metallic electrode arc is extremely susceptible to slight changes of pressure, and in consequence the unit to give the operator the best chance of making a thoroughly successful weld must be so designed as to give perfectly steady regulation and maintain a smooth, uniform arc.

It can easily be seen that these virtues are the most difficult to obtain in a single arc unit, especially when the unit has to be portable.

When a stationary plant is installed to feed a number of arcs in parallel, it is beneficial to provide a heavy flywheel, which tends to keep the speed and voltage as steady as possible, and to store up and release energy when it is most required during the striking of the arcs.

The author has thoroughly tried out the question of voltage supply, and has proved that the arc is most stable and penetrating when an ohmic resistance is used in series with the graphite electrode absorbing, as near as possible, one and a half times the voltage across the arc, and, in the case of the metallic electrode, twice the voltage across the arc.

Moreover, the arc circuit must be capable of fine adjustment.

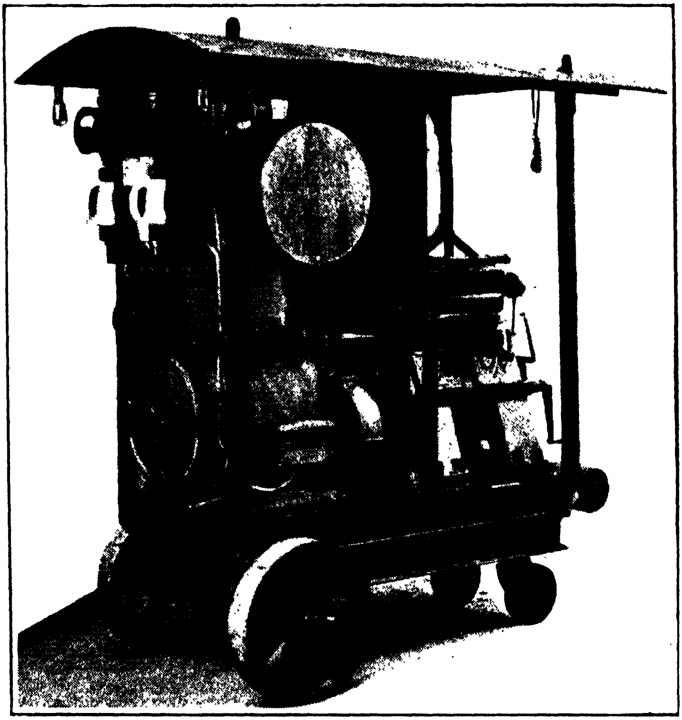


FIG. 26.—PORTABLE ELECTRIC GENERATING SET.

In the case of several arcs in parallel, the adjustment must be made by regulating series rheostats ; but in the case of single arc units the regulation may be obtained either by field excitation or by series resistance, or by a combination of the two.

When a petrol engine is used as a prime mover, a balancing relay circuit may be connected in parallel with the arc circuit, with a make-and-break switch to cut out or in the relay circuit, according to whether the arc is in operation or not. This device steadies the engine and considerably assists the governing during the make and break of the arc.

Fig. 26 shows a neat, portable petrol electric set designed specially for one operator, and is foolproof and weatherproof. The protective curtains and switchgear casings are left off for the purpose of photographing. The combined weight of the set is under 30 cwt., and it is capable of delivering 10 kw.

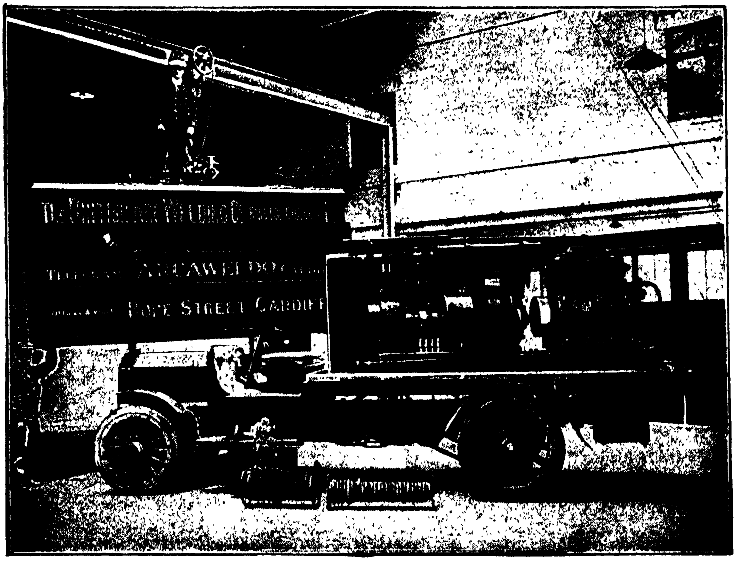


FIG. 27.—MOBILE WELDING PLANT WITH ASTER-WESTINGHOUSE GENERATING SET.

continuously, with a petrol consumption of less than 1 pint per kilowatt-hour when the plant is kept in good repair. Lighting circuits and connections for portable electric tools can be operated simultaneously with the arc.

A much heavier petrol or paraffin unit, also designed by the author, is shown in Fig. 27. The whole of the electric side was built and erected by the British Westinghouse Company. The equipment shows an Aster-Westinghouse generating set of 26 kw. normal output, designed to permit of working multiple arcs in parallel and intermittently when using either the graphite or metallic electrode. The generator is capable of allowing satisfactory operation over a considerable regulation curve, thus enabling a considerable variety of work to be carried out satisfactorily and economically. The direct-coupled exciter also provides current for lighting and for portable grinding or drilling machines. The petrol engine develops about 50 H.P. when running at 1,150 rev. per min., and is closely governed to deal with throwing on heavy overloads from no load very intermittently.

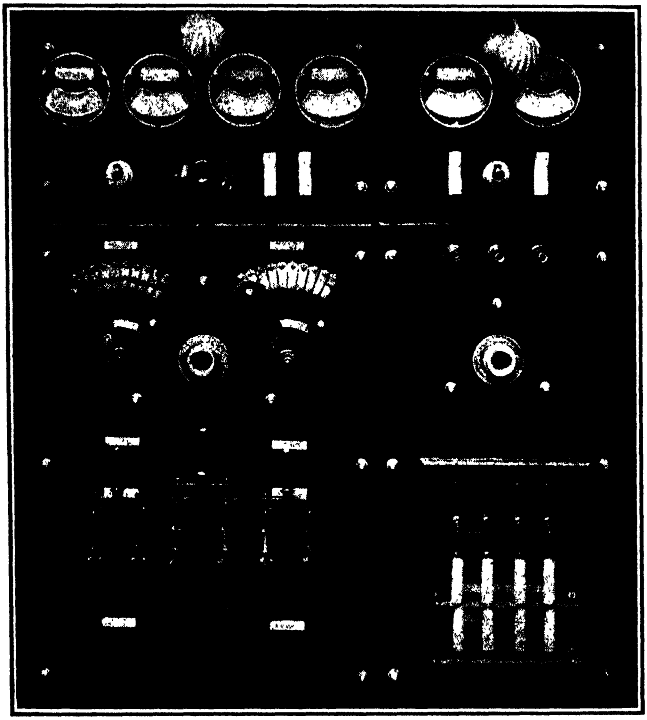


FIG. 28.—CONTROL PANEL FOR FIG. 27.

The generators, it will be seen, are all rainproof, the machines having to work on long continuous runs in all adverse conditions of place and weather. To facilitate periodical inspection, the van body is removable without disturbing

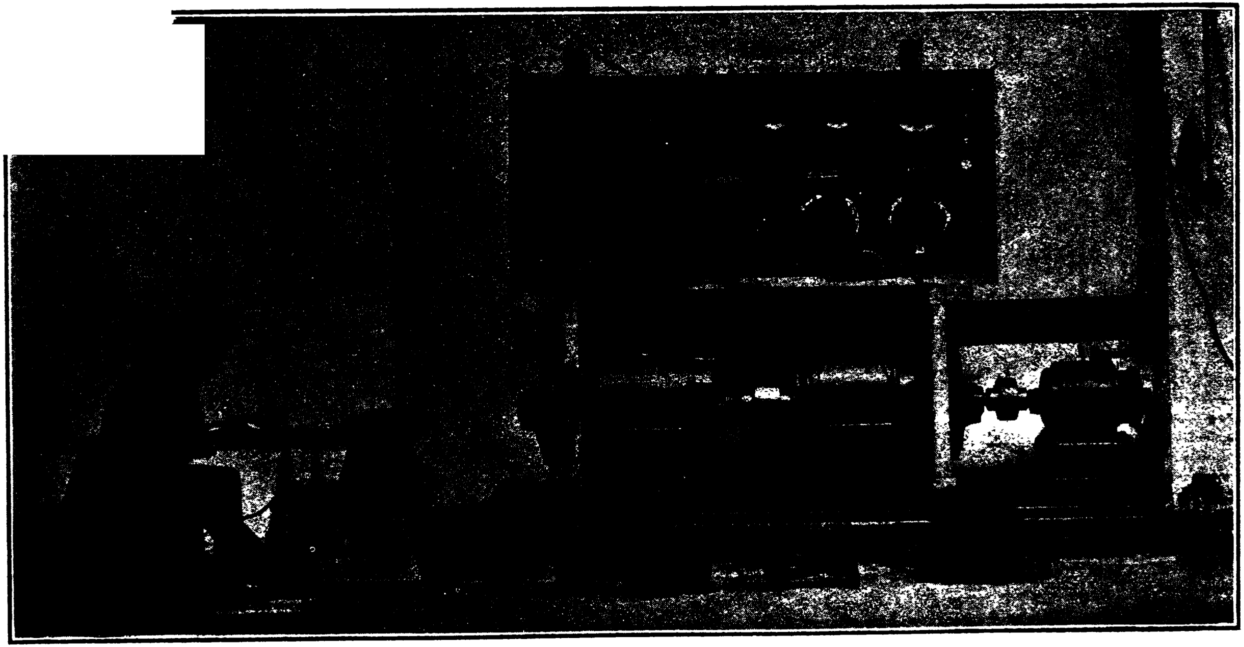


FIG. 29.—WESTINGHOUSE MOTOR-GENERATOR WELDING PLANT.

the plant in the slightest degree. The body work, which was carried out by John Norman, Ltd., of Cardiff, is all interchangeable with duplicate waggons. The cable, 550 yds. of which is carried by each wagon, has " cab tyre " sheathing, and is carried on the rollers in damp-proof boxes mounted on the side of the chassis. About 150 gallons of petrol can be carried in the tanks. The tank, seen mounted over the generator, is kept full by pumping up from a large tank beneath the chassis.

The control panels (Fig. 28) are mounted on spring framework. These are of black enamelled slate. On the right is the exciter panel and distribution panel. The left-hand panels contain the control gear for the multiple arcs. It will be noticed that the switches are double pole, two way, and the outer two switches are cross-connected respectively for reversing the polarity of the arc. The centre main switch enables the series field of the generator to be reversed, which under certain conditions is of great advantage.

The heat flowing to the article welded should be quite constant—a point of cardinal importance for reliable and homogeneous welding. It is impossible to avoid the constant lengthening or shortening of the arc, and the consequent continual alteration of the resistance while welding, resulting in a varying current and heating effect.

A generator built by the British Westinghouse Company (Fig. 29) gives all the above characteristics, and no steadying resistance is necessary in series with the arc, thus considerably reducing the power consumed. Moreover, the short-circuit current can be adjusted to less than the normal full-loan current.

The steam sets (Fig. 30) are installed on a self-propelled steam barge, and are controlled by switch gear similar in all respects to that shown above the motor generator set (Fig. 29).

In the illustration (Fig. 29) a welder is seen welding an aluminium exhaust pipe, while a gear wheel and broken shaft are lying alongside the machine waiting to be repaired.

Fig. 31 shows a diagram of the electrical connections of these machines and their characteristic curves. The machines have proved to be very flexible and extremely reliable.

Another type of electrical motor-generator set which is claimed to give the best conditions for arc welding is shown in

Fig. 32. The motor is coupled to the generator through a magnetic clutch, which is electrically inter-coupled with the welding generator. This machine is patented and manufactured by Messrs. Davies & Soames. No series resistance is used with the arc, and, by means of the electrical control of the clutch, the welding current can be set to a pre-determined value.

The diagram of connections is shown in Fig. 33. Only one operator, however, can weld off this machine, but as a one-man unit it is simple and economical.

FIG. 30.—WESTINGHOUSE STEAM-GENERATOR SETS ON A BARGE.

Messrs. Tilling-Stevens, of Maidstone, have supplied a number of their petrol-electric vehicles with some modifications to render them suitable for arc welding. The petrol engine is direct-coupled to an under-slung dynamo, which can, when the vehicle is not travelling, be run for welding, or to supply current to an underslung motor coupled to the driving axle for road travel. This arrangement gives a flexible and mobile unit, but only one metallic electrode arc can be operated therefrom.

Alternating current also may be used successfully for arc welding, with the metal electrodes system. In the case of the carbon arc, however, the carbon must always be of negative polarity. It requires rather more skill to operate off alternating current, and, further, the most useful property of the difference in temperature of the positive and negative craters

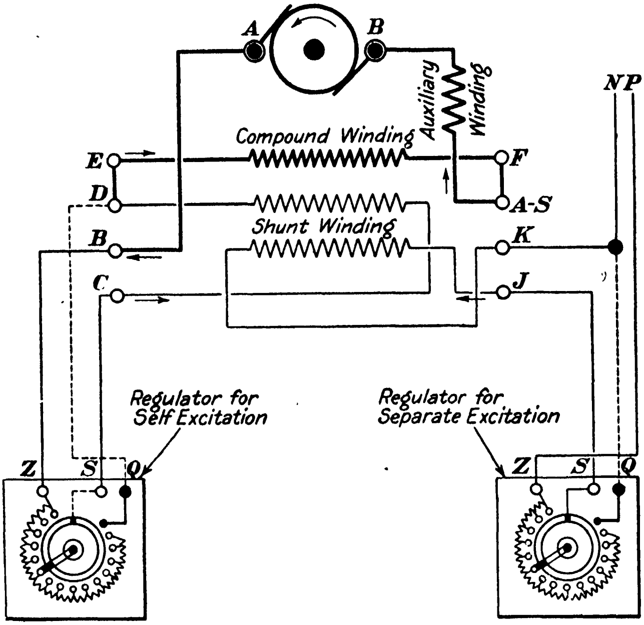


DIAGRAM OF CONNECTIONS FOR GENERATORS SHOWN IN FIGS. 29 AND 30.

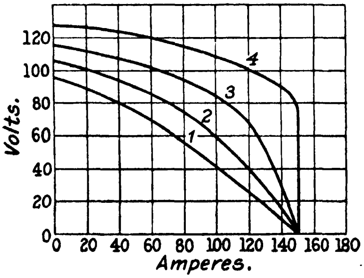


FIG. 31.—CHARACTERISTIC CURVES.

found with direct current is lost. In direct-current arc welding it has been proved that the efficiency of the weld is higher when the electrode is made negative in polarity, and hence with alternating current the resultant weld is not likely to be so satisfactory.

The author has experimented largely with both direct and alternating current, and in a general way would strongly advise direct current when possible.

Of course, the operating costs of alternating current welding are the cheaper, because current for the arc can be taken direct from a single-phase transformer through an adjustable reactance. Thus the capital expenditure may be considerably less; and, again, little energy is wasted in series resistance.

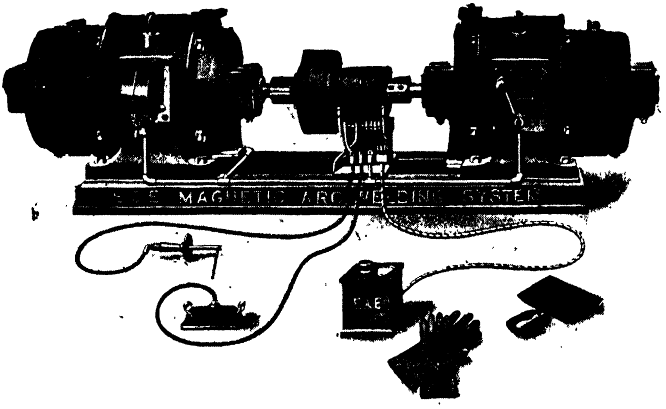


FIG. 32.—EQUIPMENT AND ENGINEERING CO.'S PLANT.

However, when the supply is a two or three-phase system, it is difficult to balance each phase of the system, and also the power factor of the system is lowered, due to the currents in the outers being out of phase with the voltages in each leg. It is advisable, and more often than not the supply authorities demand, that a motor-generator set be used, the motor being connected to each phase.

The author has found that, even with a direct-current arc, a reactance coil in circuit with the arc considerably damps down fluctuations in the welding current and voltage across the arc, and generally is very beneficial and helpful to the operator.

Before designing a welding installation, or purchasing such an equipment, it is most advisable to go very carefully into the conditions under which the plant will operate. The author has known of many failures, not due to the machinery being necessarily defective, but due to the fact that the manufac-

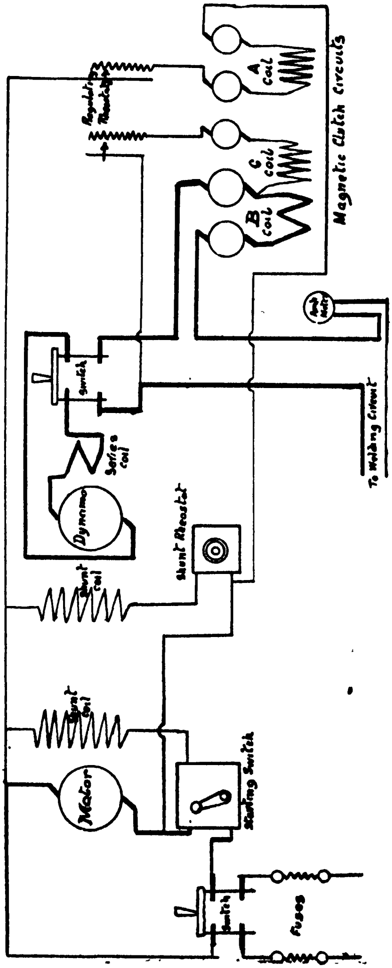


FIG. 33—DIAGRAMS OF CONNECTIONS FOR THE PLANT IN FIG. 32.

turers were not fully advised of the conditions and requirements.

The rating of a petrol engine, say, for a single arc unit, should not be less than 20 H.P., and the generator should be specified for continuous rating for 10 kw. at 60–65 volts. If the unit is required to be portable, it is advisable to have the generator totally enclosed, with forced ventilation.

When welding plant is used mostly for repair work, which more often than not is in the nature of breakdown jobs, reliability and continuity of service is more important than high power efficiency and strictly economical running.

For arc welding service, which is extremely exacting, nothing but the best materials and manufacture should be thought of; the plant and equipment must be as robust and foolproof as possible and not complicated. The author has often seen arc welding generators driven from line shafting, or mounted in a petrol wagon and driven by a chain belt from the engine clutch coupling, and almost invariably with disappointing results.

Again, a plant designed to give the best operating results with the Benardos system will not give satisfactory conditions for metallic electrode welding.

A motor-generator welding set may not be continuously rated, and gives far more pleasing operating conditions than a steam or petrol set. The set must be carefully designed, and must be robust in mechanical detail. Separate shunt field excitation in the generator is always advisable, and the regulation should be worked well over on the saturation curve.

A synchronous motor-generator set is popular with supply authorities, and the synchronous motor gives an excellent speed and load characteristic for arc welding.

In the case of alternating-current welding, the transformers should always be of the two-circuit type, with a secondary voltage of 65 volts. The reactance should be incorporated in the transformer design, the transformer having a very low power factor. The current desirable in the arc circuit can be regulated by tappings on the transformer, or by addition of series ohmic resistance, the former giving a coarse step-by-step control, and the addition of the resistance, which can also be varied, can give fine adjustments between the values of each step.

Static transformer design, however, has not yet been brought in line with arc welding requirements. So far as the author is aware, the leading manufacturers of transformers are only now seriously investigating the question of static transformers for alternating current arc welding. However, considerable improvement in design, operating and economy may be looked for in the near future.

ELECTRODES AND HOLDERS.

Figs. 34 and 39 show electrode holders, one for a graphite electrode and the other for the metallic electrode. The holder for the Benardos process is essentially the same as for the metallic electrode, but is of heavier construction and has the addition of a shield to protect the hand when using heavy currents. The exact method of gripping the electrode may differ largely, according to individual ideas. The important items are that the contact must be good, while the replacement of an old electrode by a new one must be easily

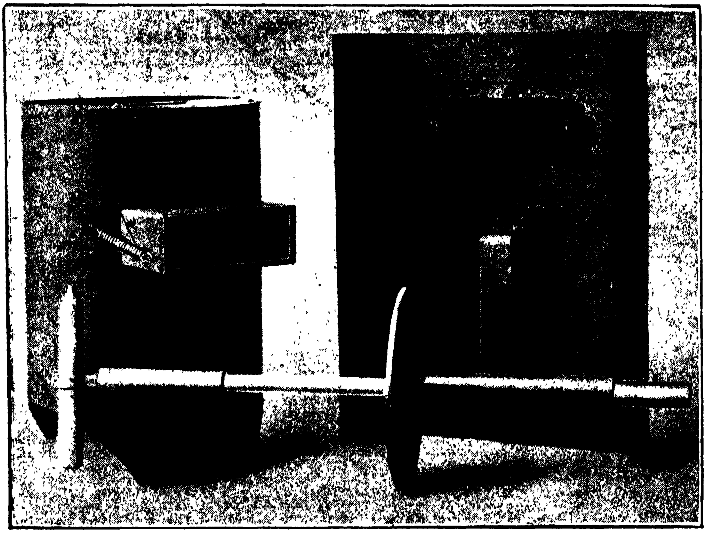


FIG. 34.—HEAD AND FACE SHIELDS AND GRAPHITE ELECTRODE HOLDER (BENARDOS PROCESS).

and quickly accomplished. The holder when held in the hand, with the cable attached and the electrode in, should just balance, thus putting the least strain on the wrist of the operator.

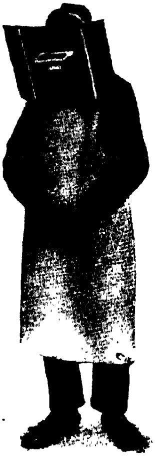


FIG. 35.

The metallic arc system does not usually require more than 175 amperes, and hence the electrode holder need not be of as heavy construction as that for the Benardos system. A disc shield is not needed, since the heat from the arc is not intense, and the radiated heat from the electrode is far less than from the carbon electrode. A spring clip with a vee groove is found in practice to work very satisfactorily, and the electrode as it is fused away can be replaced with a new one much more quickly and with greater ease than if a thumb screw or butterfly nut has to be manipulated.

It is the writer's experience that the welder will have some design of holder, which, in his estimation, is the only design, and in this matter it is tactful and wise to allow him to, and indeed, encourage him to, make his own holders.

The hand flexible cable to attach the electrode holder to the trailing cable should be very flexible, not heavily insulated, and in a length not less than 6 ft. It is most important that the operator's wrist should be as free and supple as possible. The fact should not be lost sight of that the welder's hand and wrist is actuated by very sensitive nerves, and the degree to which he can control these nerves will largely determine his skill. This fact is especially exemplified in metallic arc welding. Successful overhead welding requires very steady nerves and a very supple movement of the wrist.

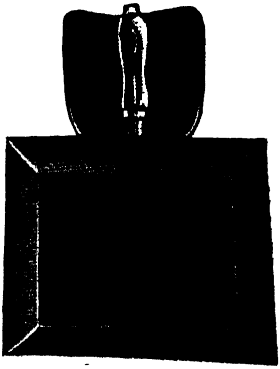


FIG. 36.—HAND SHIELD WITH CLEAR GLASS.

PROTECTIVE COVERINGS.

Arc welding, whenever possible, should be carried out in enclosures so as not to interfere with other work which is being carried out in the vicinity and to protect workmen near by or people passing by. The intense brightness of the electric arc, moreover, necessitates that the operator's head, hands, arms, and body should be thoroughly protected. The body is usually sufficiently protected by ordinary clothing, but when heavy carbon welding is done a leather apron is strongly advisable as the radiated heat and sparks will often ruin an operator's clothing and possibly scorch his flesh beneath. Leather gauntlets adequately protect the hands and wrists. The most difficult to protect adequately are the eyes, face, and neck. Coloured glasses, as used with oxy-acetylene welding, are not sufficient, as the electric arc is very rich in ultra-violet rays, which have an effect on the skin very similar to sunburn and is very painful.

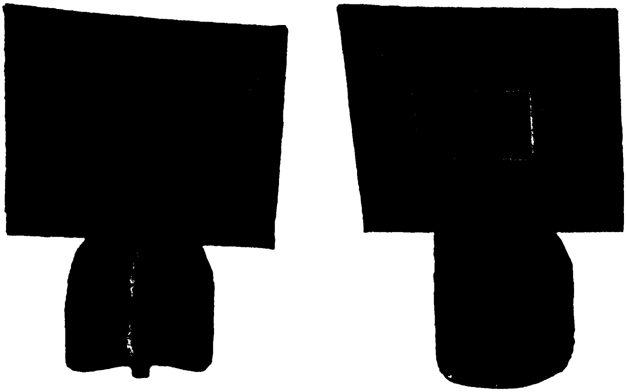


FIG 37.—HAND SHIELD WITH FIXED TRIPLE GLASS COMBINATION SCREEN.

The iron arc is especially rich in these rays, and the eyes should be carefully protected. For carbon arc welding, when an operator requires his two hands free, a head box, made to rest on the shoulders and to cover the neck and face fully, is most suitable. The head shield is best made of three-ply wood, having one sheet to form the back and one to form the front, with an observation window inserted. The sides can be of asbestos, supported on strips of similar wood to hold the back and front together. The box can be open at the top so long as it well covers the head. The window, which should be fitted with suitably coloured glass, is best made to slide in and out of a frame in a horizontal plane, having a stop on the inner side to prevent it being drawn out altogether.

Many head screens have been made and sold, of stove piping, or aluminium and micarta. However, none of these types are popular with most welders, as they are found to be too hot, or too heavy. The essential thing is that the head box should be light and cool and easily handled. The most important feature by far is the screen for the window.

FIG. 38.—OPERATOR WEARING HEAD SCREEN.

It has been found, after much scientific investigation, that the best arrangement is to have three layers of glass. The outer layer is of ordinary clear glass to protect the inner screens from the heat of the arc and from the flying atoms of hot metal ; if it is broken it can quickly be replaced at a small expense. The second layer should be of a green or amber tint, and should be selected with respect to its opacity to ultra-violet rays. The third layer should be of a neutral tint, with sufficient density of colour to reduce the intensity of the light of the arc to a comfortable degree.

For metallic electrode welding a head screen is not necessary. A flat screen of three-ply wood about 10 in. or a foot square with a centre window as above, about 4 in. square, is found in practice to meet the case excellently.

A great deal of controversy has taken place over the question of protection from the electric arc. However, after several years of practical experience of arc welding, the writer has had not one serious case of eye or skin trouble arising from practice with the arc.

If the welder in his early apprenticeship is impressed with the necessity of being careful to protect himself from the rays of the arc, he will, for his own comfort, see to it that he is provided with suitable protective gear, and quickly fall into careful habits. Of course, some people will always allow their curiosity to prevail over their better judgment, and, in spite of all warning and advice, deliberately expose themselves to the direct arc, in which case they usually get what they deserve.

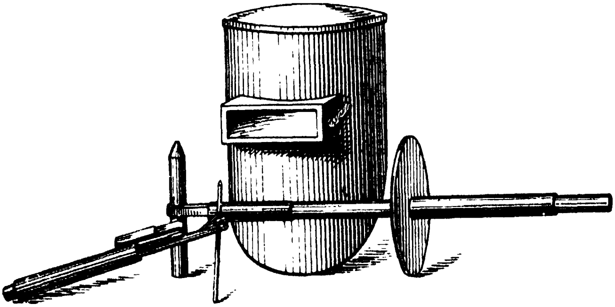


FIG. 39.—HEAD SHIELD AND ELECTRODE HOLDER.

A few hints may be of use on the general arrangement of a welding booth. For small and moderate size work a cast-iron table, firmly supported on iron trestles of about 2 ft. 4 in. high, is most useful, and if the table is about 6 ft. by 3 ft. 6 in. by 2 in. thick, with a number of ¾ in. holes drilled diagonally, also machined on its top surface, a large variety of work can be effected. Work requiring to be lined up or set in vee blocks can thus be undertaken with a nice degree of accuracy. The positive cable from the welding circuit can be permanently fixed to the table, and the table itself well earthed.

The operator is most comfortable if provided with a good wooden grid under him raised above the floor about ½ in. He can often sit to his work, which rests the body and gives greater endurance to his nerves.

These details are especially worth attending to where women operators are employed. A pair of light pulley blocks, or a light jib crane above the table, is a very useful addition.

With regard to trailing and connecting cables for arc welding "cab-tyre" sheathed cable has proved to be the only cable which meets the case in practice. The cable should be as flexible as possible and can be safely rated on a 2,000 amperes per square inch basis. The capital cost is high, but is redeemed in practice owing to its long life and mechanical durability.

The flexible hand cable may be conveniently made of dynamo flex, cotton braided, and one lapped layer of insulating tape wound round as a further protection. This arrangement affords a simple, light, and very flexible connection to the operator's electrode holder.

For all average work it is recommended to use a ½ in. graphite electrode about 8 in. long. If thicker graphite electrodes are used with currents up to 450 amperes the electrode certainly keeps cooler, but the arc ends burn away, forming like a crater, which tends to promote defective welding due to the spreading of the arc. A ½ in. diameter electrode will burn away leaving a fairly fine point, which concentrates the arc and promotes good welding.

Fine ganister or fire clay is a useful accessory. A mould round a required weld often facilitates operation and closes in the heat which should result in a softer weld. If used with care and skill a ganister mould allows of a nice soft weld being made. However, more often than not the particles from the mould get into the weld and thus undermine the advantage gained by its use.

When welding copper or its alloys, however, a mould is necessary to keep the molten metal from falling away.

SYSTEMS OF ELECTRIC ARC WELDING.

In electric arc welding there are only two systems now used to the practical exclusion of all others, namely, the carbon or graphite arc, and the metallic arc systems. The fundamental principle of each process is the same, that is, the utilization of the intense heat of an electric arc to the fusing of the metals.

The latter process may be said to be applied by three methods to-day; that is, by the quasi-arc method; the Slavianoff, or bare electrode, method; and the Kzellberg or coated electrode method.

THE CARBON OR BENARDOS SYSTEM.

This system was patented in Great Britain in 1885 by Nicholas de Benardos and his partner, both of whom were Russian engineers. The patent specification covers a wide scope, and in brief claims that the process can be used for welding, for cutting, for heating, and for perforating. The specification also mentions an appliance commonly called an electric torch. However, this ramification is generally known as the Zerener process, and will be described a little later.

In the Benardos process an arc is struck between a graphite electrode and the work to be welded, which is connected to the supply circuit as the positive. There are two reasons why the graphite should be negative. Firstly, because if it were positive free carbon would be carried from the movable electrode and contaminate the weld; and, secondly, because advantage is taken of the characteristic of the hottest part of an electric arc, which is the positive electrode. The work to be welded is invariably the greater mass, and can contain and dissipate the greater quantity of heat, which means that it requires a greater quantity of heat to bring it to, and keep it at, a welding temperature. This characteristic of an arc is of great value and importance. The temperature of the positive electrode of a carbon arc is extremely high, being estimated at about 7,500°F. It is not necessary to reach such a temperature in welding, nor indeed is it always of advantage. In fact, the sudden application of this extreme temperature prevents the process from being successfully applied to much work which would be possible if the temperature could be controlled.

However, by varying the current between 5 amperes and 550 amperes, a large variety of work can be accomplished. The current through the arc can be controlled in two ways if operating on a constant potential circuit, namely, by inserting series resistance, and by lengthening or shortening the arc. The latter method is mentioned because a number of welders take advantage of it, although the author strongly deprecates the practice. The operator should aim at maintaining a definite length of arc, a length which will give a smooth, steady characteristic.

If the arc is too short, the metal boils and splutters and blisters, and penetration is seriously affected. On the other hand, with too long an arc the arc wanders, and is unstable; the heat developed is wasted in the air, and the hot metal is more exposed to the surrounding air, which only too readily gives up its oxygen to the heated metal, which, as we have seen in a previous chapter, has a great affinity for free oxygen at a welding temperature.

The length of arc for the best working results depends upon the current used, which should be carefully adjusted by varying the resistance in series and not by varying the length of the arc. It will be found, however, that with a given terminal voltage and a predetermined current there is one value of the series resistance which will give the most steady and constant arc, and this will be the longest stable arc with that current. It may be here pointed out that this same value of current in the arc can be obtained by shortening the arc, and inserting more external series resistance, but even though the arc under these conditions is steady, the weld will be found to be much harder than if the arc is operated under the former values of external resistance and length of arc.

Operation.—The operator holds the graphite electrode in his right hand, places his head screen upon his shoulders, and holds the feeding metal in his left hand.

The arc is then struck and played round the point to be welded with a rotary motion. When the section of work under the electrode is at a suitable welding heat the metal filler is added in small increments, the arc being kept in motion until the added metal is thoroughly fused with the main body of the metal. If the operator is careless, or inexperienced, he will fail to obtain perfect fusion, by reason of adding new metal too quickly. The result will be that the new metal will run over portions of the work which have not been brought up to the correct welding temperature. This fault is very prevalent with average welders, and unfortunately the lack pany were taken out by Mr. Arthur Percy Stromenger in 1912 and 1914. The first patent is not now applied in commercial practice, owing to its obvious impracticability.

In the latter patents, the metal pencil is coated with blue asbestos spun yarn, which is a ferrous silicate, said to be a reducing agent. The fusing point of the coating is varied to suit the current density used with any particular electrode, by smearing it with a composition, such as sodium silicate or aluminium silicate.

Again, an aluminium wire can be bound closely to the iron electrode, and afterwards coated with the fluxed asbestos yarn. The aluminium is said to act as a strong reducing agent, having a special affinity for oxygen at the temperature at which welding takes place.

The proportion of aluminium to the iron electrode is usually about 2 per cent.

The action of the fluxed coating is to form a liquid flux, which, in turn, forms a pool of slag, covering the molten metal and surrounding the arc, which should be kept inside the pool of slag thus formed. The welded metal is thus well protected from the atmosphere, and moreover the flux cleanses the fused metal, dissolving any foreign elements which are thus brought to the surface.

When a layer of metal has been deposited the slag must be *thoroughly cleaned away* before another layer is deposited.

This method is claimed to facilitate the operation of welding, and that less skill is required to make a good homogeneous weld.

In the Quasi Arc system the work to be welded is connected to the negative pole of the circuit, the electrode forming the positive pole. The initial voltage advised by the Quasi Arc Company to be necessary is about 110 volts. Series resistance is used to cut down the voltage to about 30 volts across the arc, which is kept as short as possible, about ⅛ in.

CHAPTER VI

CONSIDERATIONS PREPARATORY TO ARC WELDING

WHETHER metallic arc welding is carried out by one or other of the above methods, the current used with various sized electrodes should be about the same. Table 3 gives the permissible range of current for different diameter electrodes which are on the market to-day.

TABLE 3.—*Currents Advised for Various Sizes of Electrodes.*

Size of electrodes.	Permissible current range in Amps.
No. 14 S.W.G.	12— 35
,, 12 ,,	35— 90
,, 10 ,,	75—100
,, 8 ,,	90—145
,, 6 ,,	110—160
,, 4 ,,	140—200
,, ¼ ,,	150—220
,, ⅜ ,,	230—275

Various authorities advise other current values. However, the writer has standardized the values in Table 3 after exhaustive and numerous tests with all makes of electrodes.

It will be noticed that for any one size of electrode the range of current allowed is fairly wide, and it might well be asked whether equally good results can be obtained with the use of any value of current between these limits. Possibly, yes; but here the human element is the deciding factor.

The most common error amongst arc welders is to use too high a current, for the reason, possibly, that it is easier to make a weld, or, it should be said, to manipulate the arc; and, secondly, because the metal is deposited more quickly, and consequently the operator imagines that he is making more headway. The arc with too high a current is a great danger.

The writer has always found that the best uniform welds are made with the minimum current which will properly fuse the electrode. The weld is usually cleaner, softer, more homogeneous, and consequently stronger.

However, the guiding principle should always be that the value of current used should depend upon the mass of metal in the work to be welded ; the heavier the work the higher the current necessary to bring the metal to, and maintain it at, the requisite welding temperature. The size of the electrode should consequently be chosen for the job in line with its mass and the current best suited for the job. Table 4 shows the size of electrodes used for welding various sections of plates and sheet metal.

TABLE 4.—*Size of Electrode Required for Different Thicknesses of Iron and Mild Steel.*

Thickness of metal S.W.G.	Size of electrode. S.W.G.
No. 16	No. 14
,, 14	,, 14
,, 12	,, 12
,, 10	,, 12
⅛″ plate	,, 10
3/16″ ,,	,, 10
¼″ ,,	,, 8
5/16″ ,,	,, 8
⅜″ ,,	,, 8
Or, First layer	,, 12
Second layer	,, 6
½″ plate	,, 8
Or, First layer	,, 12
Second layer	,, 6
⅝″ plate	,, 8
Above ⅝″ ,, First layer	,, 12
Second layer	,, 6
Third layer	,, 4

The figures shown in Table 4 are based on average results after numerous tests and long experience. It may be pointed out, however, that an expert welder will probably obtain equal results using a No. 8 gauge electrode when welding plating above ½ in. This fact considerably facilitates the operation on repair work, where the sections met with differ so widely. Nevertheless, it must not be forgotten that the use of one standard gauge electrode should not be practised unless the welder has had considerable experience and is thoroughly tried out.

Average values for welding mild steel plates are indicated in Fig. 40. To find the diameter of the metal electrode required, select, let us say, a $\frac{3}{8}$ in. plate, and follow horizontally to the thickness of plate curve; the vertical line through this intersection represents about 110 amperes as the most suitable current to be used with this size of plate. Then follow this vertical line to its intersection with the diameter electrode curve which locates a horizontal line representing approximately 5/32 in. diameter electrodes. In a similar manner a $\frac{1}{2}$ in. plate will be seen to require 125 amperesand a 5/32 in. electrode.

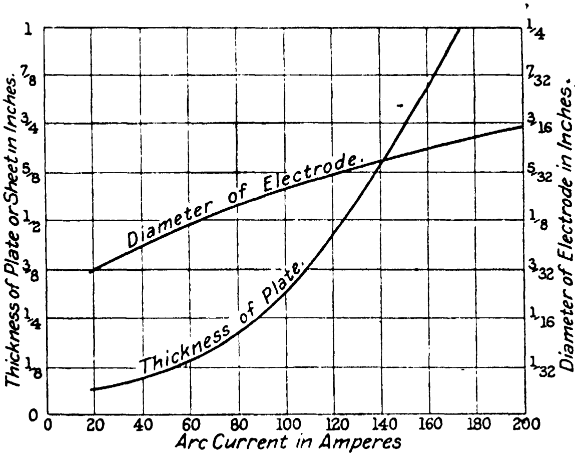


FIG. 0.—APPROXIMATE RELATION OF ARC CURRENTS AND ELECTRODE DIAMETERS.

The nature and mass of the work being welded, together with its initial temperature and capacity for dissipating heat, will considerably influence the current required. For instance, in the case of two $\frac{1}{2}$ in. plates of considerable area, such as a large tank or ship's hull plates, if lapped and requiring the caulking edges to be built up solid, or the wasted plating to be built up to the original section, as much as 200 amperes may be used with a 5/32 in. electrode, as the rate of dissipation and conduction of the heat put into the work will be large.

It must therefore be borne in mind that only approximate figures as above can be given, as no hard and fast rules can be laid down which will be applicable to a great variety of work.

For standardized shop work, such as the welding of shell casings, tanks, more or less small machine parts, etc., the above tables and curves may be followed fairly closely.

PREPARATION OF WELDS.

A weld properly prepared is half done, since the facility of execution depends to a great extent upon the arrangements made by the welder in the preparation of the parts to be joined.

Here, again, hard and fast methods cannot be advised, as in detail this preparation varies considerably with the nature of the metal, thickness of weld, and, perhaps above all, with the position and form of the parts to be welded. However, it does follow general rules which will serve as principles to indicate the method to be applied in each particular case.

BEVELLING.

By bevelling is meant the cutting to form an angle or slope. In the case of plates to be joined by welding, the bevelling of edges to be butted facilitates the execution of the weld, ensures the fusion of the metal throughout the thickness of the weld, and offers the advantage of enlarging the line of joining—that is to say, it avoids the consequences of too great a localization of the defects; and last, but not least, it permits the addition of a greater quantity of metal, of better quality than the original stock, and the better effects of deoxidizing agents and the defusion of elements destined to give to the joint the desired characteristics.

Plates of a thickness below $\frac{1}{8}$ in. are not usually bevelled on parts to be welded. From $\frac{1}{8}$ in. to $\frac{3}{16}$ in. a slightly chamfered edge-to-edge preparation, forming a V-joint of about 45 deg., is sufficient. From $\frac{3}{16}$ in. to $\frac{1}{4}$ in. the edges to be joined should be V at an inclination of 60 deg. For $\frac{5}{16}$ in., and thicker plates, the joint faces should be V, and the lower edges set about $\frac{1}{16}$ in. to $\frac{1}{8}$ in. apart, with the inclined faces at an angle of 90 deg., or each plate at an angle of 45 deg. with the verticle. Some authorities advise the form of V opening should be somewhat concave (Fig. 41, diagram *A*), and contend that this method allows of greater lateral movement at the bottom of the joint. The writer is of the opinion that the method of preparing plates as in diagram *B* is wrong, for in practice the fine edge is burned away by the action of the arc, and the deposited metal accumulates at the bottom of the V, but does not thoroughly amalgamate with the mass of the metal.

If, on the other hand, the joint is prepared as shown in diagram *C*, better penetration is obtained at the commencement. The preparation shown in diagram *A* is certainly good, but in practice, unless the joint surfaces have to be machined, hand preparation becomes expensive and takes a considerable time. The difference in ultimate results obtained at the weld with each method does not warrant the extra expense in preparation entailed by diagram *A*. When the thickness of plate is ¾ in. or over, the joint is best prepared as in diagram *D*, Fig. 41. If the two sides of the joint cannot be welded, then the joint faces are best prepared as in diagram *C*.

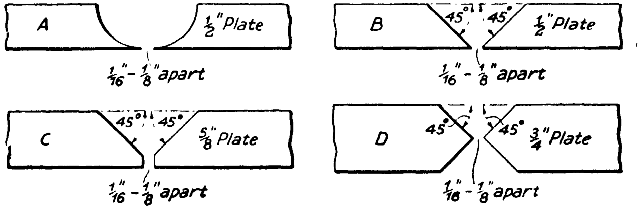


FIG. 41.—CORRECT AND INCORRECT METHODS OF BEVELLING.

The necessity for bevelling exists whatever the metal to be welded—steel, brass, copper, cast-iron, aluminium, etc. Welders who persistently weld edge to edge without bevelling thicknesses up to ⅜ in. always obtain unsatisfactory welds. Lack of penetration, adhesion, or overheating of the metal are the natural results.

CLEANING.

The faces of all metals to be welded, and the metal in their immediate vicinity—that is, where fusion takes place—should for best results be chipped or machined to bright metal. It is of the greatest importance that all work to be welded should be perfectly clean, free from oil and grease, oxide and dirt of any description. It is not fair to rely upon fluxes to cleanse the surfaces of the metal during welding.

When using the graphite electrode the work can be tilted up and impurities burned out. The frequent use of a good wire brush before and during welding is of great assistance in keeping the weld, as it proceeds, free from impurities.

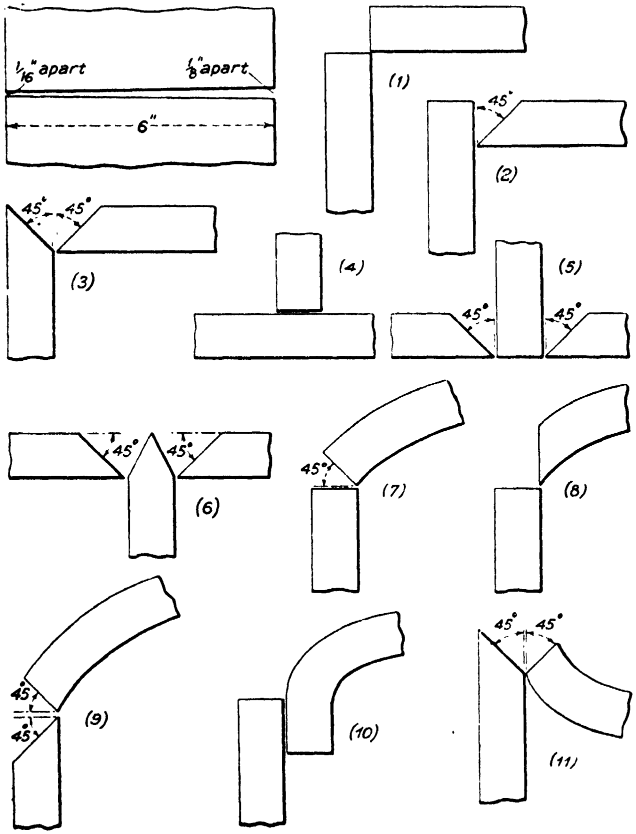


FIG. 42.—METHODS OF SETTING UP JOINTS FOR WELDING.

Before commencing to weld, careful consideration should be given to the adjustment of the parts to be joined. Unconscientious welders too often fail to take precautions to ensure this preliminary adjustment, and the solidity of the joint as well as the progress of the work suffers. Then, again, the

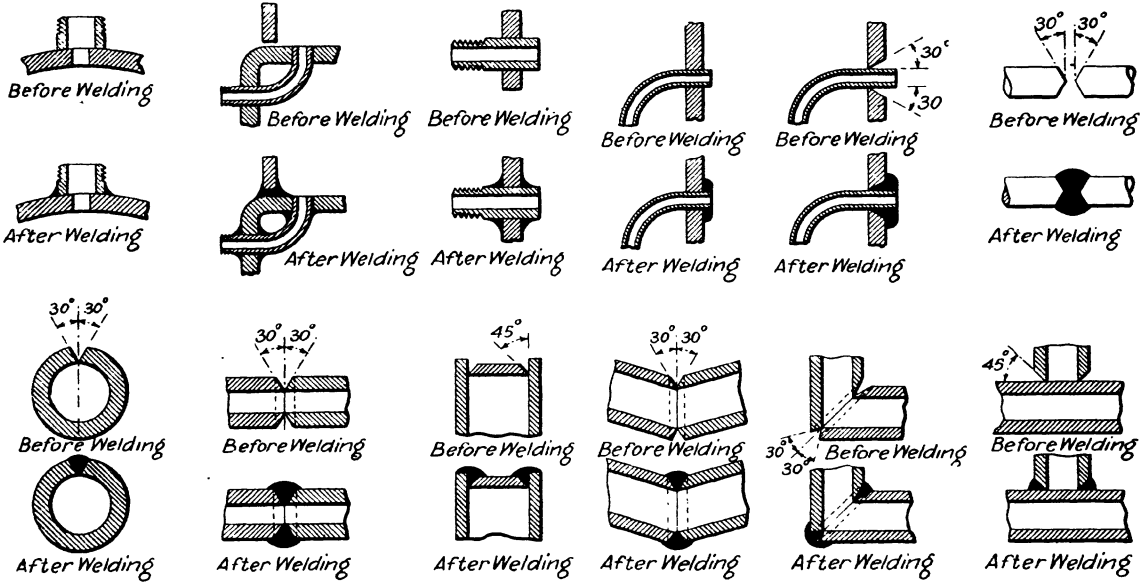


FIG. 43A.—METHODS OF PREPARING PIPING AND TUBULAR WORK FOR WELDING.

phenomena of expansion and contraction must be considered, and due measures taken to counteract their influence on the weld.

Plates at right angles can be joined without bevelling, as in Fig. 42, diagram 1. However, the preparations as shown in diagrams 2 and 3, though more costly in preparation, are obviously preferable.

The welding of T-pieces made up of two or three pieces can be done by the preparations shown by diagrams 4, 5, and 6. For plates above $\frac{5}{16}$ in. thick the arrangement shown in diagram 4 is not to be recommended, as good penetration is doubtful. The methods indicated in diagrams 5 and 6 are both good, but No. 6 requires more filling metal than No. 5. On the other hand, No. 5, though making the best job, is the most difficult of execution.

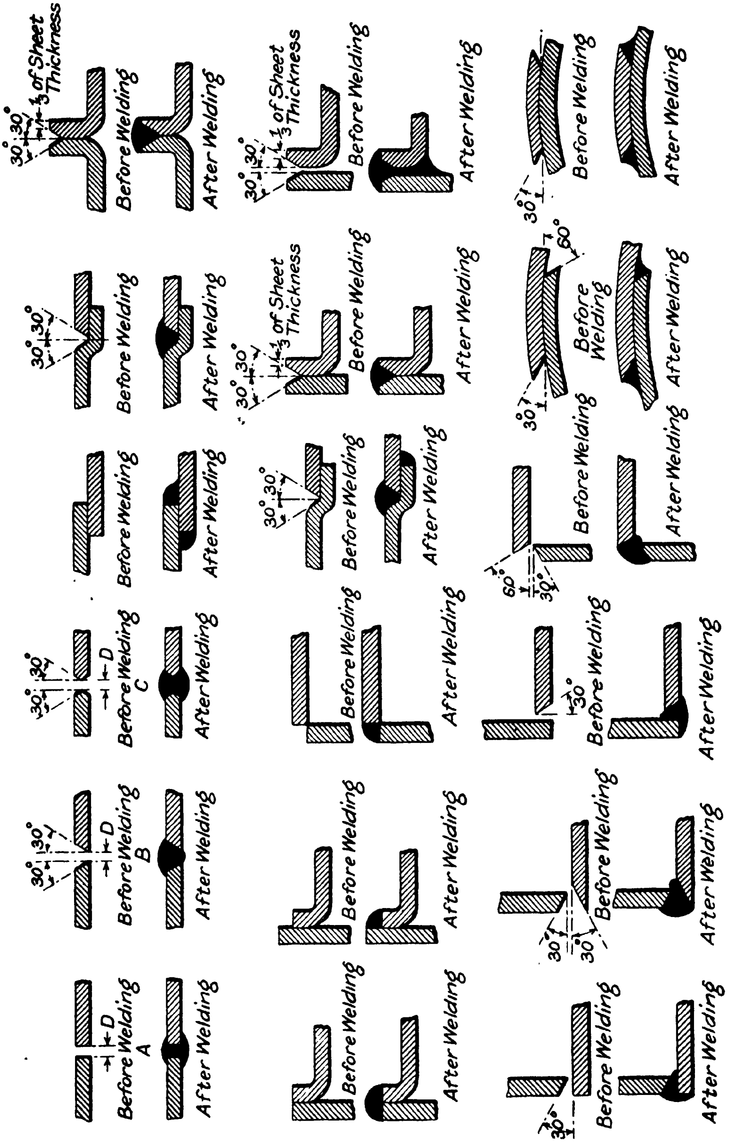
The preparation of welds of ends of cylinders, etc., depends upon the work required of them, the strain that they will have to withstand, and the purpose for which they will be used. If the vessel is to contain gas or liquid under pressure it is important that the line of welding should be arranged so that the strain is one of tension and not of bending or crushing.

The methods of preparation shown in diagrams 7 and 8 are not good, and should not be used if the pressure on the ends is great. Diagram 9 fulfils the above conditions, and is by far the best method of procedure. Diagram 10, though often found in practice, should be absolutely avoided.

A very general method of preparation, if the ends are concave, is shown in diagram 11, and for small cylinders and drums is quite sound practice and an excellent arrangement.

Finally, arrangements of various joints preparatory to welding are shown in Figs. 43A and 43B.

All the above remarks on the preparation of welds apply equally to all systems of electric arc welding.


Before Welding
A
D
After Welding
30°
Before Welding
B
After Welding
Before Welding
C
After Welding
Before Welding
After Welding
30°
1/3 of Sheet Thickness
60°
Before Welding
After Welding

CHAPTER VII.

CHEMICAL AND PHYSICAL PROPERTIES OF METALS AND THEIR INFLUENCE ON WELDING.

IRON, either pure or in the form of steel, is the material that is mostly used in metallic constructional work, and fortunately electric arc welding finds its most successful application in the working of the ferrous metals.

It will therefore be advisable to study the properties of iron and steel in some detail, and to devote the greater part of the space available in these columns to the welding of iron and steel structures.

IRON.

Physical Properties.—Iron is widely distributed in nature. It is found in the form of oxides of iron, sulphides, phosphates, silicates, and carbonates.

The bulk of the good irons of Sweden are prepared from the magnetic oxide of iron, Fe_3O_4, and the ferrous carbonate or spathic iron, $FeCO_3$, and generally are very free from phosphorus and sulphur. For this reason, and also that in the metallurgy of iron charcoal is used, which likewise is free of sulphur and phosphorus, the irons of Sweden hold a universal reputation. Iron is a greyish-white metal, ductile and malleable, and is the most tenacious of ordinary metals except nickel.

The density approximates 7.75. The melting point is about 1,500°C. Of all metals it possesses the highest degree of magnetism, which, however, disappears above a temperature of 800°C.

Its crystalline structure varies according to the heat treatment it receives, and its fibrous nature can be improved by mechanically working it either in the hot or cold state.

Iron has a conductivity of about 15 to 18 per cent. of that of silver. Iron, however, is very tenacious and possesses the most useful property of elongation to the extent of 32 per cent. before rupture takes place.

Chemical Properties.—The chemical symbol of iron is Fe, and its atomic weight is 56.

Iron is more or less strongly attacked by acids and can readily unite with most of the non-metals, such as oxygen, nitrogen, sulphur, phosphorus, arsenic, carbon, and silicon.

Iron slowly oxidizes (rusts) in a moist atmosphere; and, when heated to redness, it rapidly oxidizes in ordinary air, which process is accelerated by further heating.

The oxide of iron melts at between 1,200°C. and 1,300°C. It dissolves in the molten iron up to 1.22 per cent., which is the state of saturation.

Pure iron at its fusing temperature will not readily absorb gases, but as the content of carbon is increased the power of absorbing gases also increases. Steel will absorb 20 times its volume of gas at the fusion temperature; hence the necessity for a good flux coating, or for enveloping the molten surface in a reducing agent.

Steel, which is an alloy of iron and carbon, has widely differing physical characteristics according to the proportion of the two main ingredients, and is affected more or less by impurities, such as phosphorus and sulphur. The increase of carbon in steel reduces the ductility, elongation, and malleability, while the maximum stress, elastic limit, and hardness point rapidly increases.

It is a common error to think that iron or mild steel is the most easy of metals to weld; yet, on the contrary, they are metals which require on the part of the welder the greatest assiduity and thought. The misfortune is that the welding of mild steel is apparently so simple, and gives results sufficient for joints to be passed without trouble. Welders are often ignorant of the phenomena produced during the melting of the metal under the electric arc; they believe their welds are perfect because they look well. They become self-satisfied, never doubting their ability, and undertaking with a light heart welds which require precisely those qualities of the metal which are lost in fusion. Hence the failures, even accidents, which may occur a considerable time after the work is done, through defects in the weld.

Where repair work is to be effected by electric arc welding, or indeed by any system of welding, only proved, highly competent welders should be employed, as power plant users are always exceedingly discouraged by failures after welding, which are more often than not due to faulty workmanship; and failures and accidents consequent upon want of skill on the part of the operator give very great set-backs to the profession as a whole, and prevent machinery users and others from taking advantage of welding systems where considerable time and expense could be justly saved.

As we have previously explained, oxidation is one of the welder's worst enemies. It is difficult, if not impossible, to prevent oxide being formed, and if it becomes imprisoned in the weld it is impossible for the joint to have the strength and elasticity of the original metal, the very properties which are particularly required.

WELDING OF CAST IRON.

Even to-day many experienced welders, and a large number of engineers, hold the opinion that good and reliable welding of cast iron is next door to impossible, at least in so far as the art of to-day is advanced. Nevertheless, let it be known that these only lack technique and greater reflection. In point of fact the welding of cast iron is far easier than of all other metals, inasmuch as, in the case of good workmanship, the piece repaired is generally of superior quality to the rest of the piece, and surely more than this cannot be desired.

Considering everything, and after reflection on what has already been said upon the science of metals and their behaviour under heat, it will be seen that the difficulties to be overcome are neither very numerous nor insurmountable.

GENERAL PROPERTIES OF CAST IRON APROPOS OF WELDING.

Cast iron is a compound of carbon and iron in which the proportion of carbon lies between 2 and 6 per cent. Cast iron cannot, we all know, be forged or worked, and in consequence articles of this metal are shaped or obtained by casting in moulds.

Commercial cast iron usually contains from 3 to 4 per cent. of carbon, which may be present in very different states, either combined with the iron or dissolved in the metal, giving same a very hard nature; or, again, in the free state in the form of particles of graphite distributed in the mass of the metal.

The former variety is known as "white iron"; it is hard and difficult to work.

In the latter variety the metal is soft and easy to work; it is known as "grey cast iron."

In nearly every case the line of weld requires to be worked after completion of welding, and hence the new metal should be of *grey iron*.

Now, it is well known that rapid cooling of the fused metal tends to enhance the combination of the carbon with the iron, resulting in the formation of "white iron." On the other hand, slow cooling or reheating tend to bring about the precipitation of carbon flakes, and thus to produce "soft grey iron."

If silicon is introduced into the weld in the form of ferro-silicon it naturally displaces the carbon, combining with the iron in its place, and forces the carbon to be precipitated in the form of graphite. Manganese, on the contrary, opposes the precipitation of graphite and assists the formation of "white iron."

Thus, to produce a soft weld that can be filed and machined it is only necessary to bear in mind three principles:

1. Slow cooling;
2. Introduction of silicon in the added metal.
3. Total absence of manganese.

The latter point is emphasized for the reason that this element is very common in cast iron, in sufficient quantity to promote the formation of "white iron" during the execution of the weld.

The melting point of cast iron is about 300°C. lower than the melting point of pure iron, being between 1,030°C. and 1,200°C. The oxide of iron formed when welding cast iron melts at about 1,300°C. to 1,400°C., and hence is not easily dispersed as in the case of pure iron or steel by the action of the arc. The oxide forms a crust or an agglomerate which settles on the surface and hinders the execution of a good weld.

Obviously this oxide so formed must be destroyed by a suitable cleaning flux. Further, this oxide tends to interpose itself in the weld, and to prevent the perfect joining of the fused portions of the metal, and to destroy to a considerable degree the action of the silicon.

It is not necessary for welders to prepare their own flux, as the mixing of fluxes is now done commercially and expertly, and they can be obtained of suitable compositions for most metals.

Many welders are in favour of using borax, but this practice cannot be recommended, as borax lacks the important quality of neutralizing the decarbonization of the cast iron which takes place through oxidation. Also the flux powder (generally used) should never be thrown into the molten metal while welding ; the filling rod, warmed and dipped into the flux, will provide all that is required.

Cast iron is one of the worst conductors of heat, and is devoid of elasticity and elongation before rupture. If, therefore, the shape of the piece to be welded opposes free play of the metal on heating or cooling, it is necessary to foresee in what direction contraction or expansion stresses will cause ultimate fracture.

The prevention of contraction breaks can often be avoided by locally heating the piece to be welded at opposite points and uniformly cooling. When the article is made up of different sections of metal, or has heavy bosses or lugs, rims, etc., it is best to pre-heat the whole mass, execute the weld quickly while the mass is at a cherry red, and cool off very uniformly and slowly.

It is most important that all cold draughts be excluded, as they prove extremely troublesome.

When the article can be pre-heated the weld can be done with advantage by graphite arc process.

However, many jobs can be done successfully without pre-heating if the chill is first taken off. The metallic arc is here the better system to adopt, though thin metal can often be best welded with the graphite arc, using anything from 5 to 50 amperes, according to the delicacy of the work. Of course, the filling rod must be in proportion to the current used.

Arc welding can score over all other systems of welding cast iron in that, by means of the metallic arc system, work can be performed in any position relative to the operator.

In certain special cases of heavy sections, a sound weld is rendered more certain by previously inserting a few staggered steel or iron studs, which will materially assist when the weld contracts from the state of fusion.

Unfortunately, cast iron is far more affected in its internal mass than pure iron or steel by gradual deterioration. For instance, many cast iron articles are used in processes which necessitate their being frequently heated to a high temperature. When this is done the cast iron undergoes internal oxidation, and frequently it is found, when preparing an article for welding, that the nature of the metal has been altogether changed. It is useless to try and weld iron of this kind, for it will absolutely refuse to be welded.

Cast iron which has been constantly subjected to salt water deteriorates internally, and the welding of such iron is also impracticable.

Again, certain cast irons known as " tenacious cast irons " are most difficult to work, and in most cases prove impossible to weld.

Fortunately, however, these unweldable cast irons are the exceptions and not the rule. Nevertheless, it is wise to know of their existence, and to be prepared for failures in the actual execution of welds.

PROPERTIES OF COPPER AND COPPER ALLOYS.

The autogenous welding of copper and its alloys has received very little attention up to the present day, and, so far as the author is aware, is practised very, very little commercially. However, copper can be welded successfully if its technique is thoroughly understood ; and, indeed, excellent results can be obtained with both pure copper and many of its alloys. It may be of interest if a few facts and hints are given.

As is well known, copper is a metal of reddish colour, and when fractured it shows a rose hue. Yellow copper contains oxide of copper in the dissolved state.

Copper is a hard metal, tenacious, having a tensile strength at ordinary temperature of about 33,000 lb. per square inch (which rapidly diminishes under the effect of heat) ; elastic up to 40 per cent. elongation and has a density of 8.9.

The presence of sulphur, antimony, or lead in the metal makes it brittle, and copper oxide dissolved in the metal causes it to lose many of its good mechanical characteristics.

The heat conductivity of copper is very high, which makes the welding very difficult, as the contraction after welding is very rapid ; and, as we have pointed out, at this temperature, the tenacity of the metal is very low, and thus contraction fractures along the line of weld are difficult to avoid.

For these reasons, if possible, the articles should be preheated to dull redness before welding is commenced ; the final execution of the weld should be as rapid as possible, and the whole mass slowly cooled.

The line of weld should be briskly hammered, taking great care that the metal is not too hot. This mechanical treatment restores the nature of the copper, which is almost destroyed by the action of the heat.

The oxide of copper formed while welding is readily dissolved in the molten metal, and hence a flux is not of great assistance. A filling rod should be used which has a strong reducing agent incorporated with it.

Again, copper, when in the state of fusion, very freely absorbs gases which promote blow holes on cooling. Phosphorus incorporated in the welding rod prevents the absorption of gases, and, in addition, acts as a deoxidizer.

WELDING OF COPPER AND COPPER ALLOYS.

The parts to be welded should be prepared in much the same way as that given for iron and steel, and according to the methods we have described in the general section on " The Preparation of Welds."

However, as copper in the state of fusion is very viscus, it is necessary to support the under side of the weld in case of fracture or such like, or if a new part is to be built on, a mould should be built round the portion to be built up to prevent the added metal from running away. If the resultant weld is to be perfectly homogeneous and free from blow holes, the parts under weld supporting material or mould must be very clean and free from organic matter.

We emphasize again that the fusion of the metal should not be commenced until the edges of the weld and their vicinity have been raised to a high temperature.

The welding should be undertaken with the graphite arc, which should be longer than would be used for welding iron, and should be freely played about the line of weld in a circular motion to prevent the burning of the copper. The fusion of the part to be welded and the melting of the phosphuretted welding rod should be undertaken simultaneously in a regular and continuous operation. The welding rod should never be allowed to be added in drops.

As soon as welding is commenced the completion should be attained as rapidly as possible, taking care to regularly fuse both the edges, and to add new metal in regular increments; also to add excess metal to permit of working the line of weld afterwards.

All special forms of welding rods should be strictly avoided, and nothing but *pure* phosphuretted copper should be used.

The secret of success very largely depends upon the preheating of the article to a high temperature, maintaining the heating after the operation and very slow and uniform cooling. After welding and cooling in this manner, the line of weld, which will consist of coarse cast metal, should be vigorously hammered together with the metal adjacent to the weld, which, due to the high temperature to which it has been subjected, is highly crystallized. If the sections are heavy, the hammering can be done hot, though care must be taken that the temperature is only moderate.

After this mechanical treatment the copper is best heated to about 500 deg. and then plunged into cold water.

The author has had many welds made on copper strictly following the above directions, which give a tensile test of from 31,000 lb. to 33,000 lb. per square inch, with an elongation of from 20–27 per cent.

WELDING OF BRASS.

The general principles and precautions indicated for the welding of copper apply equally to the welding of brass. However, the welding of brass is accompanied by three distinct phenomena which render the successful operation a very much more difficult one than in the case of pure copper.

These are:

1. Absorption of gases.
2. Volatilization of zinc, tin, or lead.
3. Oxidation.

The welding rod should be very pure, and contain a very small amount of aluminium, which is necessary to deoxidize the welds. A cleaning flux is again indispensable, which, in addition to the properties already indicated, should have the function of dissolving the alumina produced during the deoxidizing process. One of the best fluxes for copper and its alloys is made up of a powder of chloride of sodium, sodium borate, and boracic acid.

The conductivity of brass as compared with that of copper is appreciably lower, and its tenacity when heated is higher. These two facts considerably help the operation of welding.

It is a good scheme to coat very thinly the exterior of the filling rod with the flux before welding, and thus ensure a clean and uniform application of the rod and flux. The same mechanical and thermal treatment of the weld is advisable for brass as for copper welds.

BRONZES.

Bronzes are alloys of copper and tin. The malleability of bronze decreases with the increase in the content of tin, and above 20 per cent. of tin the elongation is negligible. The heat conductivity of bronze is considerably less than that of copper, and when heated its strength almost completely disappears; thus great care must be taken to support the weld and not overheat.

The same cleaning flux used for copper and brass can be used for bronze. The filling rod should be of first class manufacture, and contain a small quantity of phosphorus and aluminium.

The best advice the author can give for the general procedure in the welding of bronzes is to treat them as cast iron and to carefully follow the directions laid down for the welding of that metal.

CHAPTER VIII.

APPLICATIONS OF ELECTRIC ARC WELDING.

THERE is no longer any question that large savings in time, labour, and money can be secured by electric arc welding, not only when used to repair work, where it is finding an ever-widening field of application, but also as a definite manufacturing process.

Its application is daily extending in carrying out such work as:

- Varied kinds of ship construction and repair work.
- Repairs to steel castings.
- Repairs to steel and iron forgings.
- Repairs to cast iron and malleable iron castings.
- Manufacture of pipes of all shapes and sizes.
- All kinds of tramway repair and constructional work, both factory and track work.
- Manufacture of tanks, barrels, seamless boats, drums, cylinders, boilers, steel wagons, motor cars, vats for breweries, converter shells, annealing pots, transformer housings, oil refinery equipment, cotton mill machinery, fans and blowers.
- Repairs to rolling mill wobblers and pinions, repairs to automobile parts, toothed wheels, building up of worm shafting, and many other phases of engineering construction far too numerous to mention here.

The Steel Barrel Company, of Uxbridge, have extensively applied the Benardos system to the manufacture of steel barrels, tanks, and drums of all sizes and for numerous purposes, such as the transport of motor spirit, acetone, sulphuric acid, oils, bisulphide of carbon, benzol, petroleum, and many chemical products.

A longitudinal joint being welded by the carbon arc is shown in Fig. 44. The sheet steel is rolled into shape, fixed on the anvil with the free edges abutting, and the joint heated with the arc to a fusion temperature, new metal being added to thicken up the joint.

When the desired degree of heat is attained, the welder puts

FIG. 44.—CARBON ARC WELDING.
(A) DRUM ; (B) and (C) CLAMPS ; (D) ELECTRODE HOLDER ; (E) SWAGE.

aside his electrode, applies the swage, and toughens up the joint. The method of fixing the ends is interesting. The ends are slightly dished, flanged outward (generally), inserted into the ends of the cylindrical body, and a band of like material dropped over the outside and inside of the flange flush with the ends, and the four thicknesses fused and welded together.

To prove the efficiency of this system and the strength of the welds, a drum (Fig. 45) was dropped several times from a height, culminating in 19 ft., on to a solid iron bed. The bung, a wooden shive knocked lightly into a 1½ in. tapered neck, did not move. Fig. 46 shows the drum after being thus dropped seven times. There was not found to be the slightest leakage or fracture.

Recently Mr. T. T. Heaton, of the Steel Barrel Company, carried out drastic tests on electrically welded steel plating.

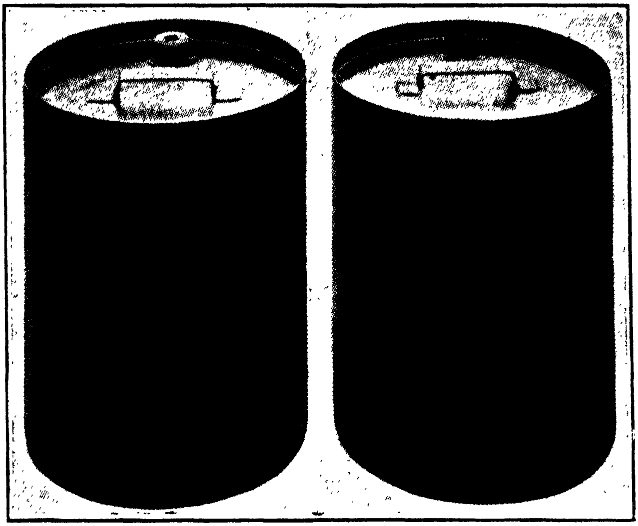


FIG. 45.—DRUM BEFORE. TESTING.

A number of cylinders, about 1 ft. long by 10 in. outside diameter, of open hearth mild steel of 26 tons per square inch, tensile strength, ⅜ in. thickness, were welded longitudinally. The cylinders were compressed by means of hydraulic dies to about 4½ in. diameter at one end. The cylinders were reduced in three stages, the first compression being very severe, reducing the diameter by 4 in. All the cylinders (Fig. 47), welded by first-class workmen, withstood the operation quite successfully. Mr. Heaton points out that mild steel plating of about 3 mm. to 4 mm. in thickness can be welded, including working the metal, so as to be sound and petroleum-tight at the rate of 2.76 minutes per foot of weld, and other fused welds at the rate of 1.22 minutes per foot of actual welding. Carbon electrodes of 15 mm. diameter are consumed in welding $\frac{1}{8}$ in. thick mild steel at the rate of 8 in. per 50 ft. of welding.

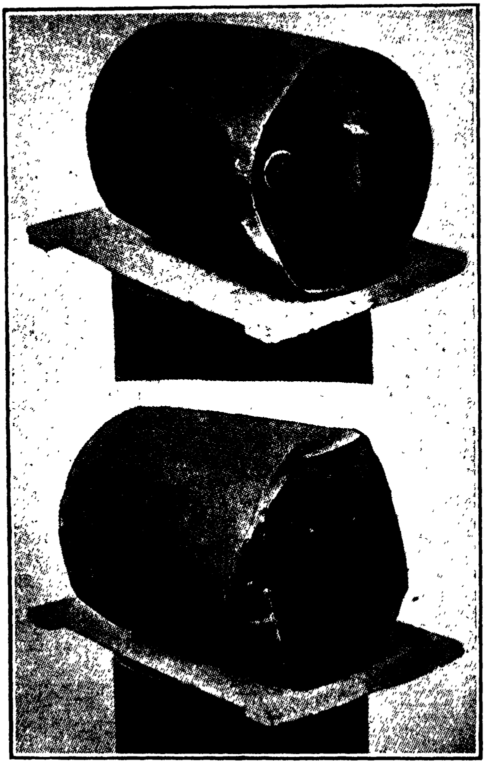


FIG. 46.—DRUM AFTER TEST.
Capacity—5 gallons.
Dimensions—15 in. long by 12 in. diam. by 19 S.W.G.
Weight—Empty, 10 lb.; full of petrol, 49 lb.

Another important and successful application of the Benardos system is to be found in the attachment of flanges, branches, bends, " T " pieces, etc., to steel and iron tubes or pipes. This process was first adopted at Halesowen, Birmingham, about 1891, and has been in constant use ever since.

The method of welding flanges to steam pipes is shown in Fig. 48. The flange is prepared in such a way that a " V " shaped groove is left on the inside, as shown in diagram *b*, extending nearly through the thickness of the metal. The flange is then shrunk on a tube, with flat face outwards, or at the end of the tube, and is carefully let into the required position (diagram *c*).

Small pieces of steel are laid in the " V " and then welded in by the flame of the arc. The weld should be well hammered between each beat. The welding is carried out right round the back of the flange, and is filled up sufficiently to form a radius of about 1¼ in. to 2 in. The flange is thus solidly built to the tube at the back (diagram *d*).

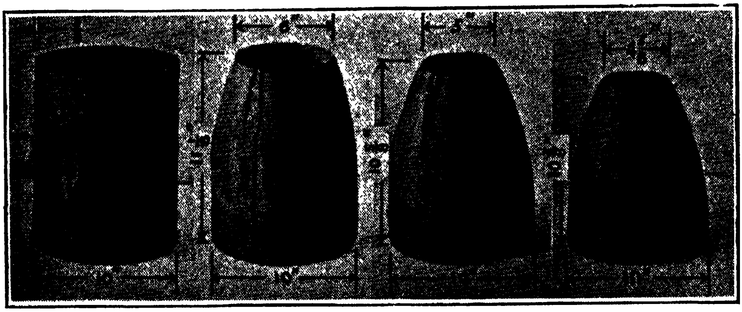


FIG. 47.—BENARDOS ELECTRICALLY WELDED CYLINDER AND RESULTS OF THE THREE COMPRESSIONS.

The tube is then up-ended (diagram *e*) and the outer side of the flange is welded to the tube. In this operation the arc itself is utilized to burn out the metal down to where the first weld commenced; this portion is then filled up and welded as before.

Branches, outlets, " T " pieces, etc., are welded to tubes in very much the same manner as flanges. The branch is cut off to the required length, and a hole is burned into the tube by means of the arc. The branch is then fixed into the hole and welded in the manner already described. All kinds of bends, expansion pipes, tees, etc., can be welded to steel pipes with the most excellent results.

It is highly important that a fairly long arc (2 in. to 3 in.) should be used, thus obtaining a better diffusion of the heat.

Figs. 49A and 49B illustrate sundry small articles welded with the carbon electrode, while Figs. 50 A, B, C and D, and Fig. 51 show illustrations of pipe work made up of pieces and welded by means of the metallic electrode method. Whichever method is used, the preparation and procedure is similar.

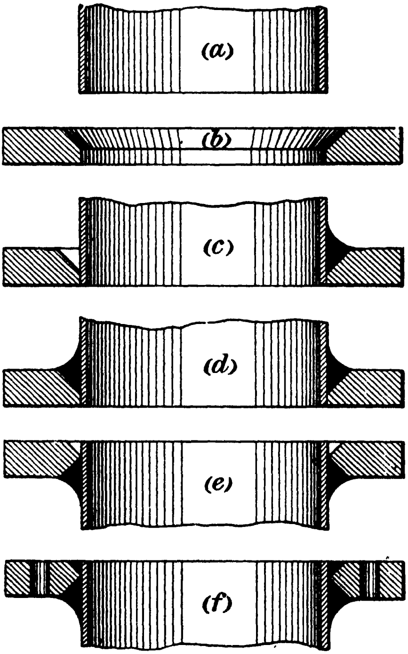


FIG. 48.—FLANGE WELDING ON STEAM PIPES.

STRENGTH OF ELECTRICALLY WELDED FLANGES.

An 8 in. iron pipe, ¼ in. thick, with flanges electrically welded, when tested to destruction at Lloyds' Proving House, Netherton, broke in the body of the pipe at over 88 tons, the welded part remaining intact; a similar pipe of steel broke in the welded part of the flange at over 101 tons. These tests were tensile only, and were carried out with the view of proving the absolute soundness and consequent strength of the flanges electrically welded on. For this purpose special tackle was made. A blank flange with an eye-bolt attached was secured to each flange of the pipe, and the chain of the testing machine was connected with the eye-bolts at each end, with the results given.

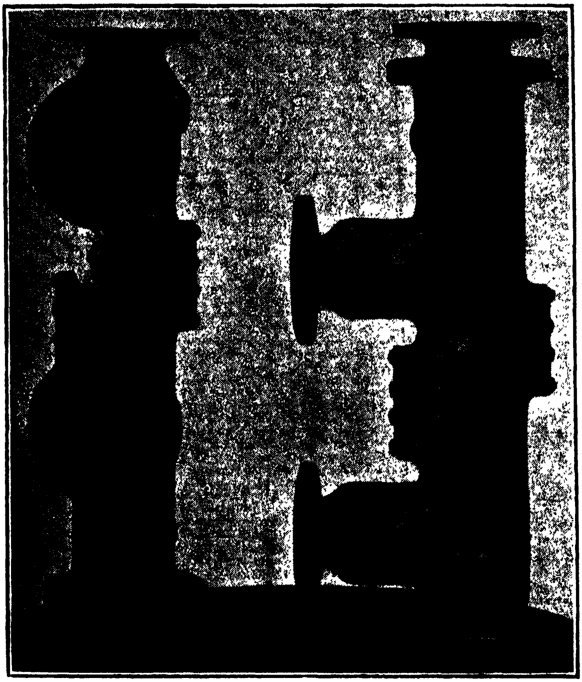


FIG. 49A.—ARC WELDED PIPEWORK.

Fig. 52 illustrates a petrol tank of 1,000 gallons capacity completely constructed by the graphite arc welding process. The tank was extremely robust and sound, with no vestige of leakage.

As examples of heavy repair work which can be quickly and successfully undertaken with the graphite arc system, Figs. 53 and 54 are of interest. Fig. 54A shows a heavy casting set for

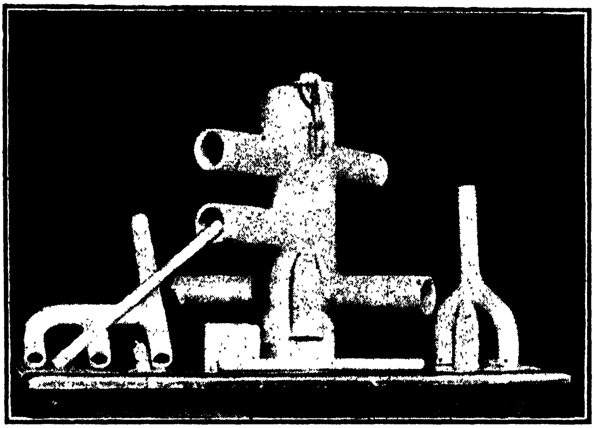


FIG. 49B.—ARTICLES WELDED BY MEANS OF A CARBON ELECTRODE.

welding up by this process, while Fig. 54B shows the same casting after the welding is completed.

The anchor in Fig. 55A had been welded up under the steam forge three times and failed to pass Lloyds' tests each time. The author's firm undertook to repair the anchor electrically, and chance that the metal in way of the fracture had not been perished. The fracture was cut out (Fig. 55B) entirely by means of the electric arc, and welded up and slightly reinforced, as shown in Fig. 56, with great success. The anchor weighed over

FIG. 50A.—THIN METAL PIECES WELDED WITH METALLIC ELECTRODES.

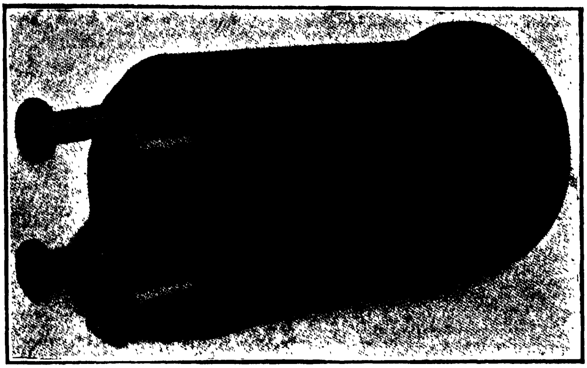


FIG. 50B.—LARGE TANK WITH ALL SEAMS AND JOINTS WELDED WITH METALLIC ELECTRODE

7 tons. A large number of anchors are dealt with in this way. Sometimes a large or small piece breaks off one of the flukes, and a new piece can be forged or cast and welded on, so that it is very difficult to tell that any repair has been made. Again, often the eye, for the shackles give out; these can be cut out by the arcs, welded up solid, and even reinforced.

Again, the electric arc welding process has proved of the greatest value to tramway systems, especially during the war, as by its use it has been possible to repair badly worn sections of the track, and thus avoid the laying down of new rails.

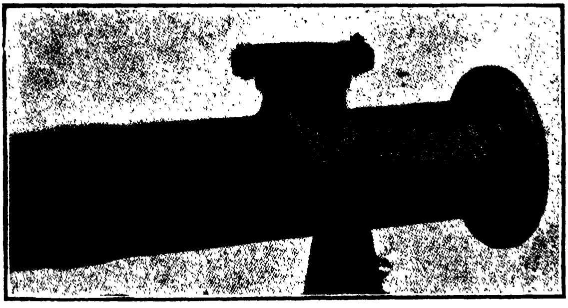


FIG. 50C.—TWO PIECES OF PIPE WELDED TOGETHER AND THE BRANCH PIPES WELDED IN PLACE.

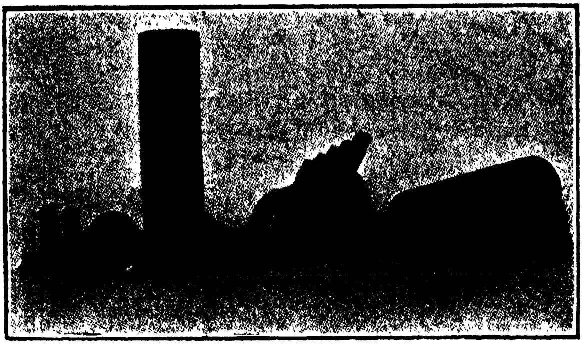


FIG. 50D.—HEADERS WITH BRANCHES WELDED IN BY METALLIC ELECTRODE.

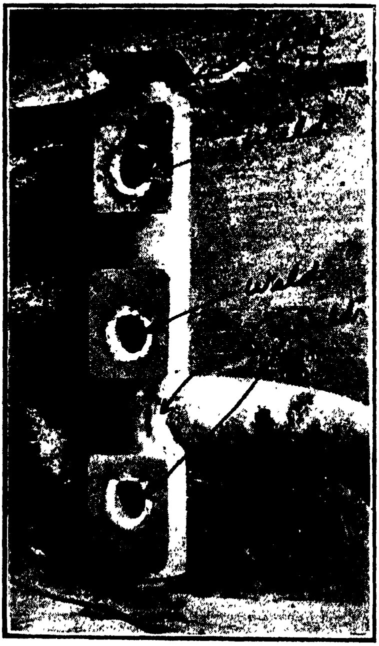


FIG. 51.—WELD MADE BY COATED METALLIC ELECTRODE.

For building up hammered joints the process cannot be excelled, and a large saving in track maintenance is thus effected. Many corporations now bond their rails by means of arc welding.

For these purposes a light, portable motor generator set can be used, the motor being run off the trolley wires. When the plant is not required for track work it can be used in the tramway shops for carrying out all sorts of repairs, such as building up worn brake bars, cracked gear cases (Fig. 57), motor frames (Fig. 58), flata on steel tyres, broken or cracked suspension bars, worn bolt holes, couplings, etc. (Fig. 59) can all be made good and put into commission again.

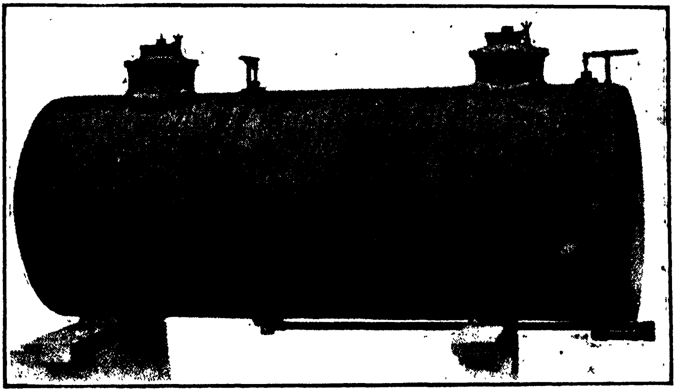


FIG. 52.—WELDED PETROL TANK FOR ROAD MOTOR TANK WAGON, CAPACITY, 1,000 GALLONS.

Armature or gear shafts can, when worn, be built up and returned to size (Fig. 60).

A common accident to motor yokes or frames is for the bearing brackets to break off, due to the gears fouling. These can be welded on again quite successfully (Fig. 59), thus saving time and valuable castings.

However, most of this work should only be performed by thoroughly experienced operators, as no doubt of reliability is permissible.

It can easily be seen that arc welding can be of great service in the railway shops.

Figs. 61, 62, and 63 illustrate repairs being effected to locomotive frames. Fractures in the main frames, horn cheeks, wheel rims, and spokes, etc., can first be cut out by the graphite arc and afterwards welded ; and, if convenient, reinforced by either the graphite arc system, if the parts are disassembled and can be turned about, or by the metallic arc in position.

Fig. 64 shows the main driving wheel of an Atlantic type locomotive, in which three of the spokes gave way by cracking in the neighbourhood of the coupling rod crank pin boss.

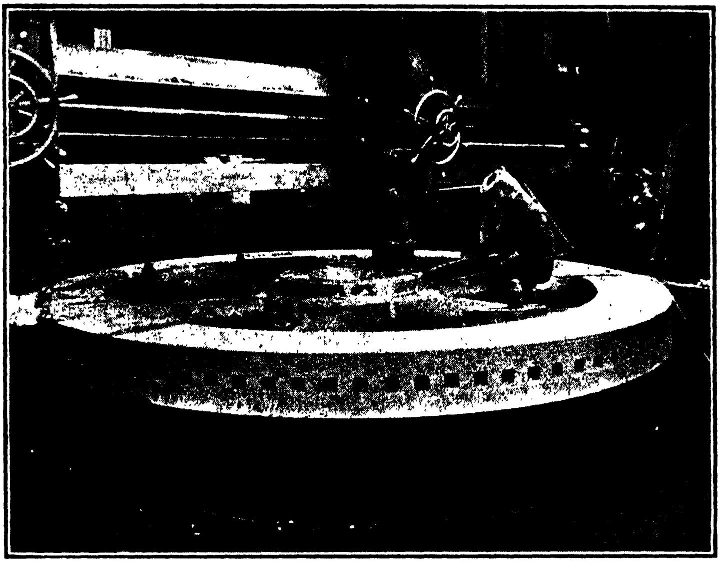


FIG. 53.—AN EXAMPLE OF HEAVY MACHINE REPAIR WORK.

These were repaired as indicated and strengthened at the ends as shown.

As already can be seen, the field for arc welding is very extensive, and, in point of fact, many thousands of pounds' worth of material is scrapped every year by machine shops, foundries, and manufacturing establishments, a very large portion of which can be very cheaply and successfully reclaimed by resorting to electric arc welding.

FIG 59.—REPAIRS TO MISCELLANEOUS ARTICLES RECLAIMED FROM THE SCRAP-HEAP BY ELECTRIC WELDING.

The firm with whom the writer is connected cannot weld these in sufficient numbers to satisfy the demand for repairs.

Motor car cylinders, crank and gear cases, clutch dogs, axle casings frames, gear wheels, and shafts can be very successfully welded by means of the arc processes.

Broadly speaking, the same kind of material is used for filling in as in the structure worked upon, but it is preferable to secure material containing certain elements which help to increase the strength or softness of the weld.

Metallic pencils of alloys of steel, such as manganese steel, nickel steel, vanadium steel, silicon steel, etc., are excellent electrodes for reinforcing certain welds.

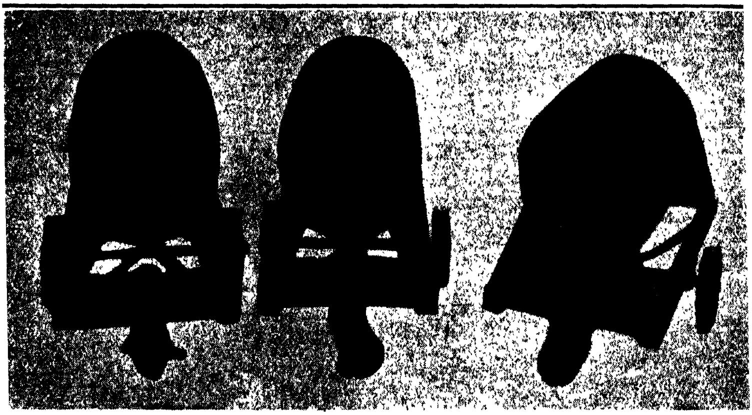


FIG. 60.—WORN ARMATURE SHAFT ENDS RE-BUILT UP BY THE ARC PROCESS.

In general, the process of preparing the fractures or joints for welding is the same in all cases—namely, preparing a cavity large enough to allow for working the metal before starting to weld.

Cracks in plating or structures must first be chipped on to the solid metal with a chisel or burned out with the graphite electrode, and a V groove formed which is filled in with the most suitable metal. With heavy sections it is sometimes necessary to make more eleborate preparations, and for cast iron and special shapes it is advisable to pre-heat parts, or, if possible, all of the piece before welding.

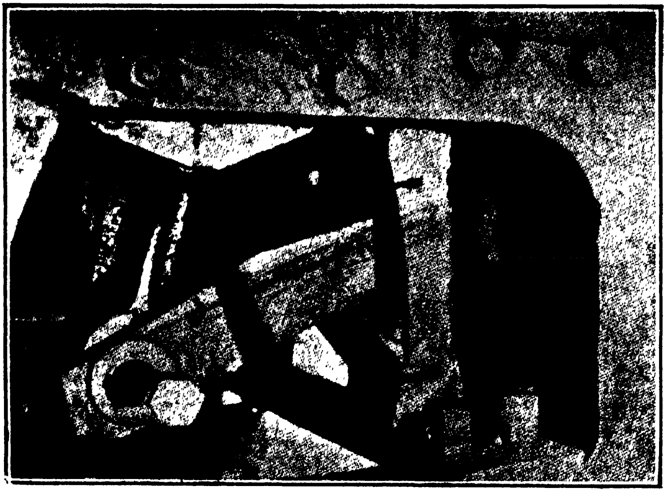


FIG. 61A.

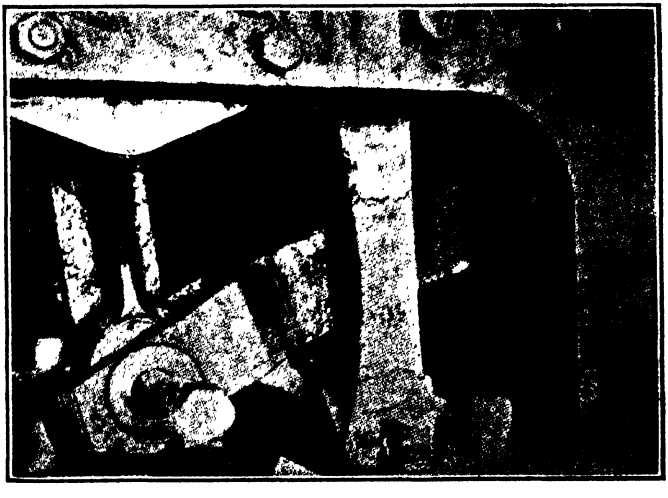


FIG. 61B.—LOCOMOTIVE FRAME REPAIRS.

Cast-iron welding can best be carried out with the graphite electrode, and a cast-iron rod containing an excess of silicon, and such other elements as are liable to volatilize at the high temperature, should be used for filling in or building up as may be required, though in certain special cases of the building up process the metallic electrode may be used with advantage.

It is very desirable to pre-heat cast-iron articles to a dull red heat before welding, and then to re-heat them afterwards, both for the purpose of reducing stresses due to shrinkage when cooling, and consequent liability of cracking, and also to ensure a good soft weld which can be easily machined. Salt or borax is a good flux to use in the welding of cast-iron. Copper can also be welded with the graphite electrode ; the additional copper used as filling material can be literally puddled in. It is necessary to prevent the molten copper from running out

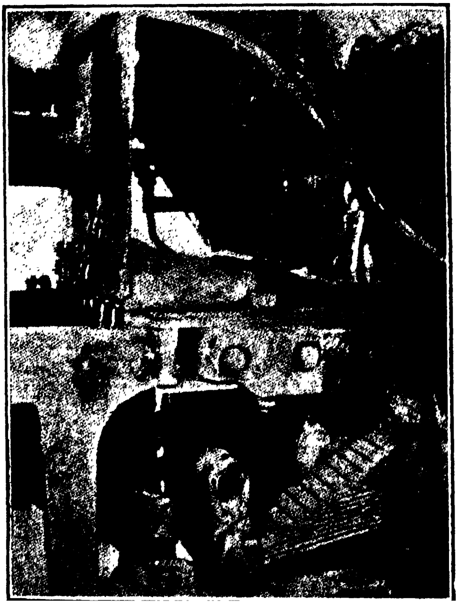


FIG. 62A.—BROKEN LOCOMOTIVE FRAME BEFORE WELDING.

of the joint, and this will necessitate, in some cases, building a temporary mould of clay or other material round the joint.

A good flux is desirable, such as a mixture of sodium phosphate and boracic acid. Great care is needed not to burn the metal, and copper welds should be upset and worked with a hammer to restore the fibre and prevent crystallization.

Copper alloys, such as brass, manganese-bronze, phosphor-bronze, etc., are very difficult of treatment, because the zinc, manganese, etc., burn very rapidly, leaving only copper in the weld.

FIG. 62B.—LOCOMOTIVE FRAME REPAIRED.

Fig. 72 is a drawing of a broken cast-steel crankshaft which is one of several successfully welded with the metallic electrode by the author's firm. The dotted lines show the shaft preparatory to welding.

Electric welding has done much to lessen the cost and time for repairs, but perhaps in no sphere is this more manifest than in marine engineering, and in boiler repair work generally.

The following illustrations are a few examples of repairs effected by the author's company which were carried out to the

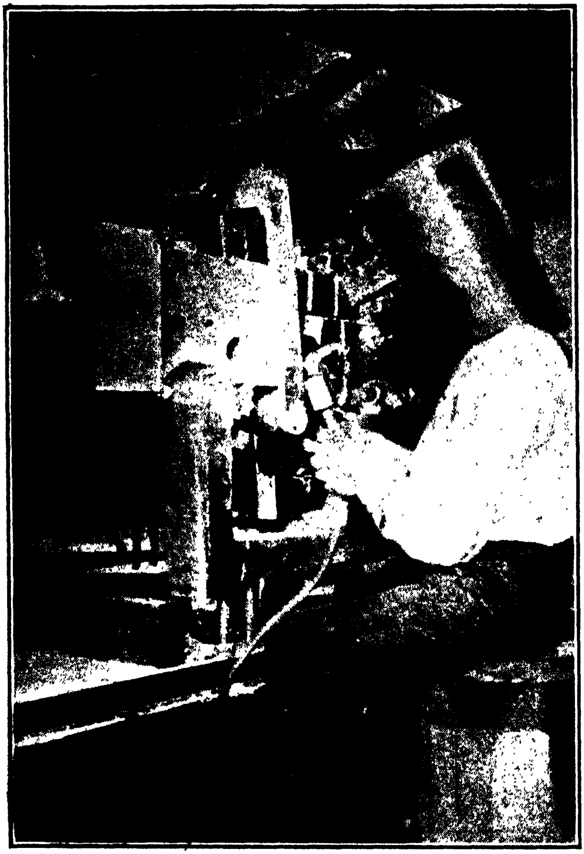


FIG. 63.—CARRYING OUT REPAIRS TO A LOCOMOTIVE.

satisfaction of the Surveyors of the Board of Trade, Lloyds, Register, and the various classifications and boiler insurance societies, which is the best guarantee of their reliability and efficiency.

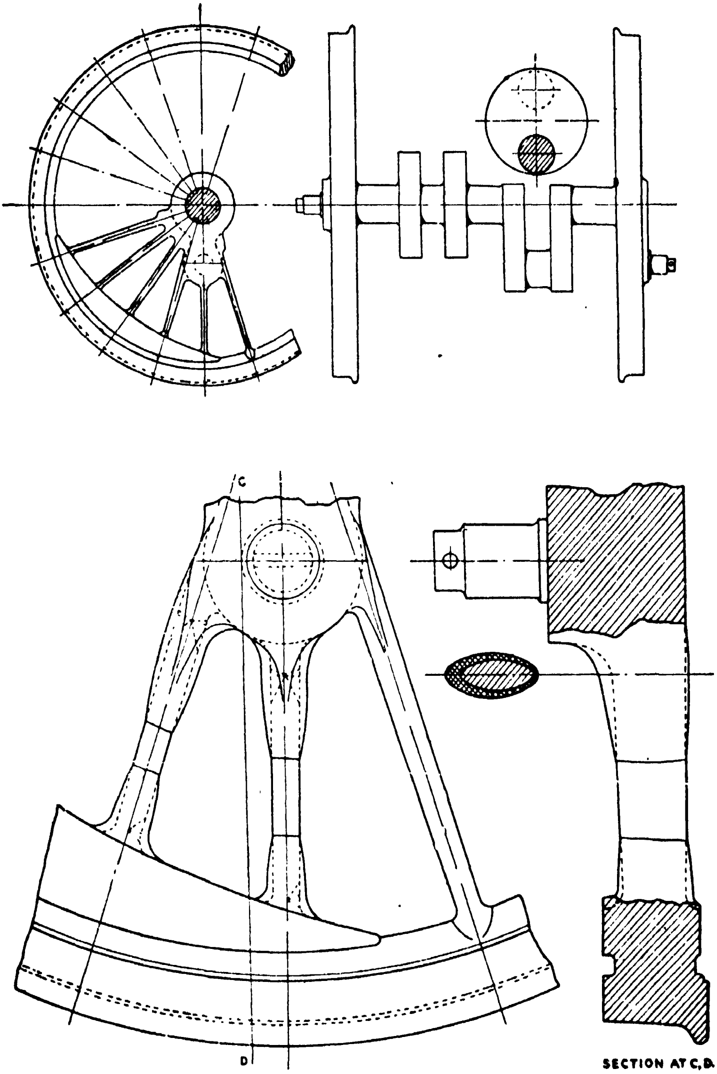


FIG. 64.—LOCOMOTIVE WHEEL SPOKES WELDED.

Fig. 73 illustrates repairs effected to the main boilers of a large cargo vessel. The fractures, extending circumferentially in the radius flange of the front ends of the boilers, were cut out to the full section of the plating, V-eed out and welded up as shown, partly from the waterside and partly from the outside. The landings were then built out and extended over the fracture, so as to strengthen the whole flange; also the wasted and defective plating of, and in the way of, the manholes was built up solid as shown, and the doors re-fitted.

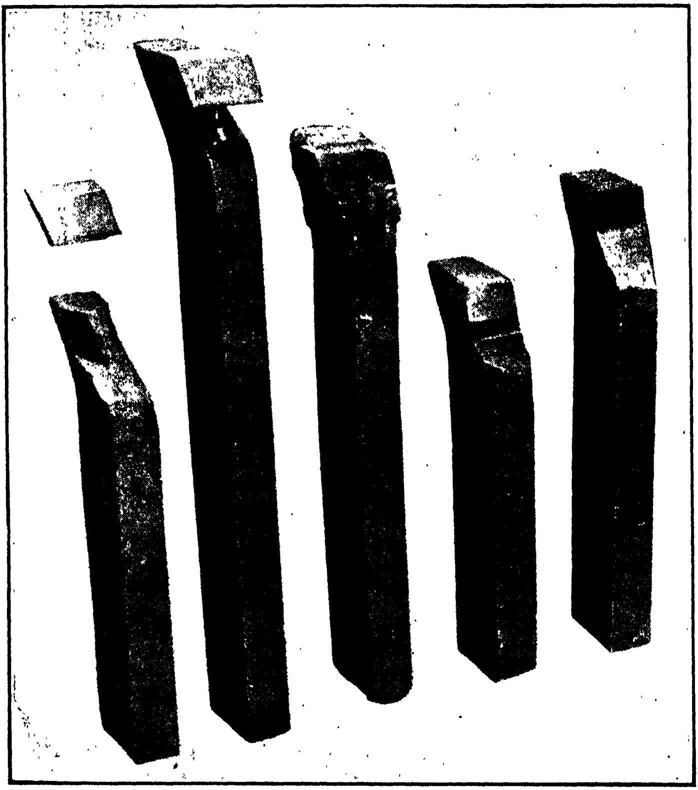


FIG. 65.—HIGH-SPEED MACHINE TOOL TIPS WELDED ON TO IRON SHANKS.

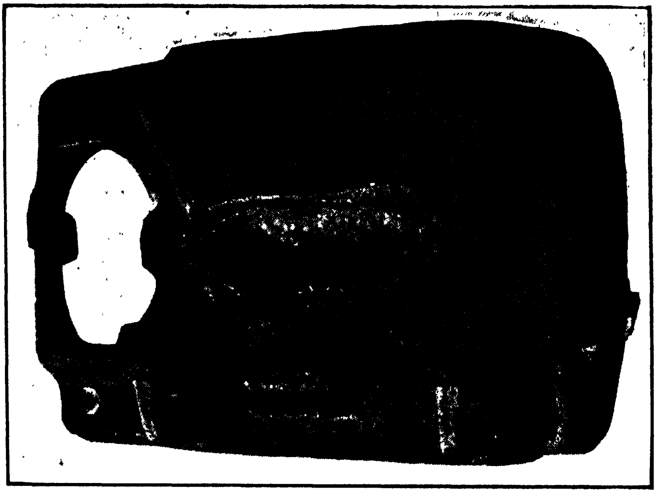


FIG. 66.—DEFECTIVE STEEL ELECTRIC MOTOR CASTING.

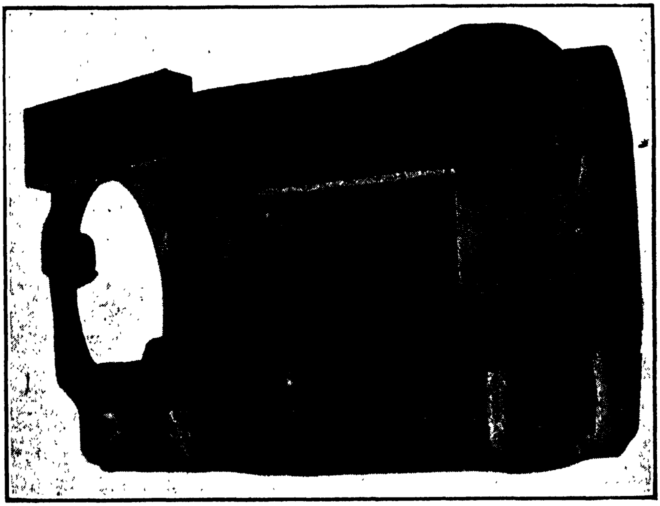


FIG. 67.—DEFECTIVE PORTION OF ABOVE CASTING CUT AWAY AND NEW PORTION PREPARED FOR INSERTION.

In boiler work and general repair work the metallic arc system reigns supreme, as work can be done in situ and in any position so long as there is sufficient room for an operator to work.

An expert welder can carry out extraordinary repairs in places which seem almost impossible. Recently the writer's company reclaimed four large Lancashire boilers at a colliery in the Forest of Dean. The boilers had been worked with very bad water, with the result that in four years the expansion rings and flanges on the water side of all the sections of the furnaces had wasted away to such an extent that the boilers were condemned absolutely by the insurance society.

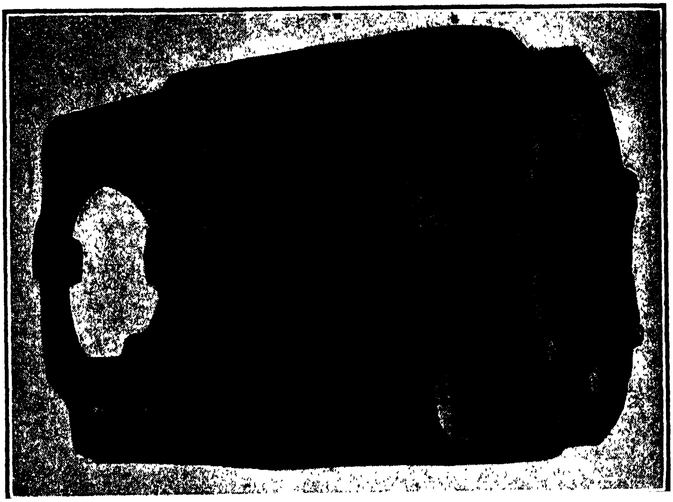


FIG. 68.—NEW PORTION WELDED IN SOLID IN CASTING IN FIG. 66.

In addition, the furnace plate had pitted and wasted in the narrow spaces very deep. The radius flanges on the water side of the front end and back end shell plates in way of the furnace ends had grooved abnormally.

Serious wastage had taken place in all parts of the water spaces. These boilers were repaired in situ entirely by the electric arc process, with no removals whatsoever, at a cost of between £300 and £500 each. The work took three months. On completion, a cold water test of two and a half times working pressure (200 lb. steam) was put on the boilers by the insurance surveyers; and, after a thorough internal and external examination each boiler was passed for full working pressure.

A new boiler was quoted at £1,800 and delivery uncertain.

FIG. 69A.—HEAVY ROLLING MILL PINION: WORN PARTS RE-BUILT.

A great variety of work on boilers, land and marine, is being carried out every day. This work consists of welding up defective and wasted landings and caulking edges, cutting out and welding up solid lap fractures in seams, fractures in furnace plating, fractures in shell plating, which commonly occur in the radius flange of the front end plate round the furnace fronts (Fig. 74 A—E).

Owing to the strong objection to placing a riveted seam

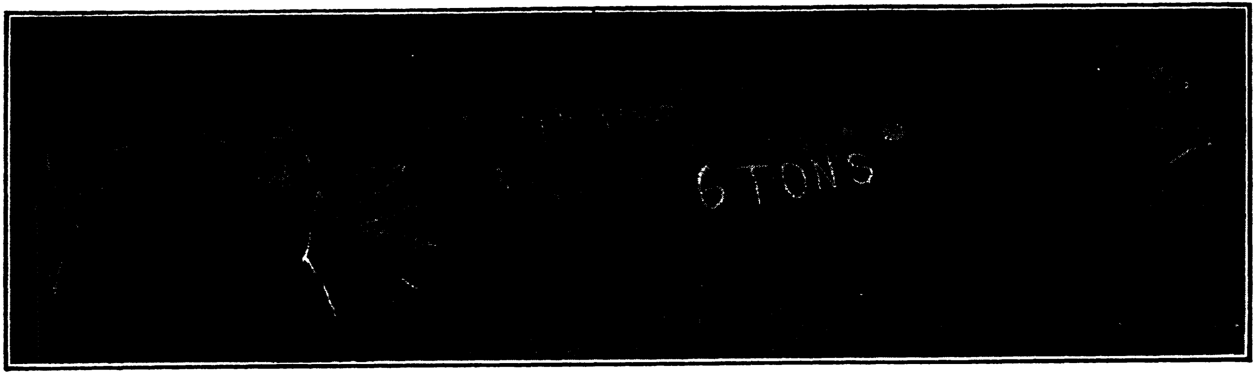


FIG. 69B.—HEAVY ROLLING MILL WOBBLERS RECLAIMED BY BUILDING UP WORN PARTS AS INDICATED BY LINES.

in a position where it will be subjected to high temperature, it is now common practice to butt weld in new plates to the backs of combustion chambers, weld in new lower tube plates, &c. (Figs. 75 A and B, and 76). In fact, wherever serious wastage has taken place, the defective area of plating can be cut away and new portions of plating welded in (Fig. 77).

It is of considerable interest and importance that, although the author's company have effected many thousand pounds' worth of boiler repair work every year, they have never had to cast a rivet before or after welding.

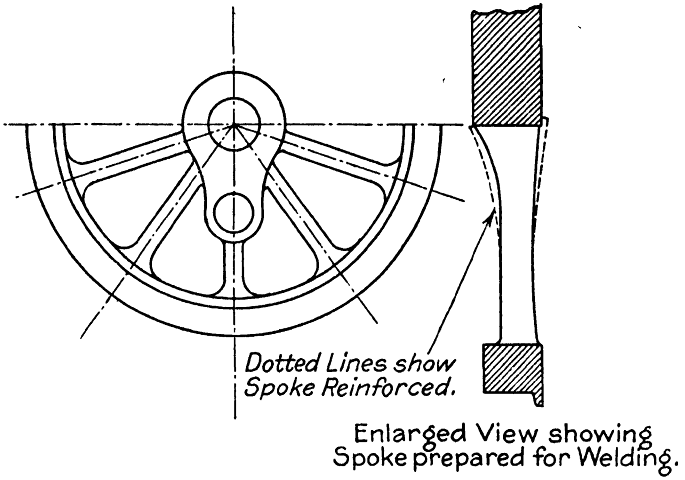
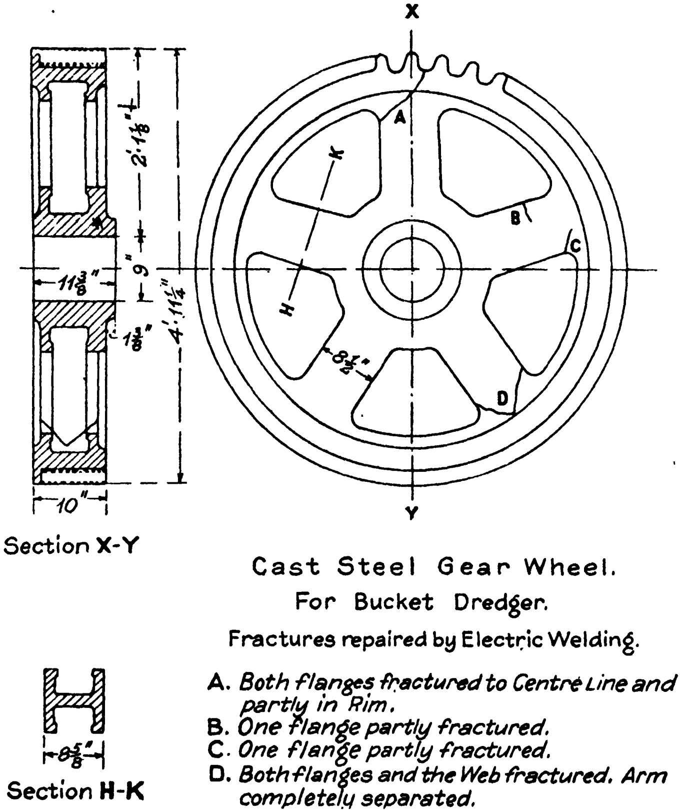


FIG. 70.—FRACTURED LOCOMOTIVE WHEEL WITH SPOKES REPAIRED AND REINFORCED BY THE ELECTRIC ARC WELDING PROCESS.

The welding of a plate into an existing structure or plate rigidly supported on all sides is a most scientific operation, but can be done by the electric arc system with entire success by complete knowledge of the technical difficulties and expert workmanship.

With the electric metallic arc the temperature, though extremely high, is very localized, and the surrounding plating or metal is in no way detrimentally affected right from the line of the weld. However, the effects of the expansion and contraction have to be very carefully studied, especially in commercial repair work, as the conditions of working are rarely those calculated to assist the operation. Varying atmosphere, temperature, cold draughts and generally unfavourable hindrances are the usual order of daily practice.

Any suggestions and advice of procedure which could be set out here might prove in practice dangerous rather than helpful, owing to the fact that what might apply in one case may be inadvisable in another case. Each individual case must be examined and treated on its own merits.



Cast Steel Gear Wheel.
For Bucket Dredger.
Fractures repaired by Electric Welding.

A. *Both flanges fractured to Centre Line and partly in Rim.*
B. *One flange partly fractured.*
C. *One flange partly fractured.*
D. *Both flanges and the Web fractured. Arm completely separated.*

FIG. 71.

However, when butt welding two plates or portion of plates, or welding in insert patch plates, the edges to be joined should be chamfered at about 45 deg. each, and kept apart about ⅛ in. Should the weld be a long one, say over 1 ft., the edges should not be paralleled and the spacing should be increased from ⅛ in., increasing ⅛ in. per foot of weld (Fig. 42). The expansion should be allowed to work all one way, and the welding is best commenced and carried through with as few breaks as possible.

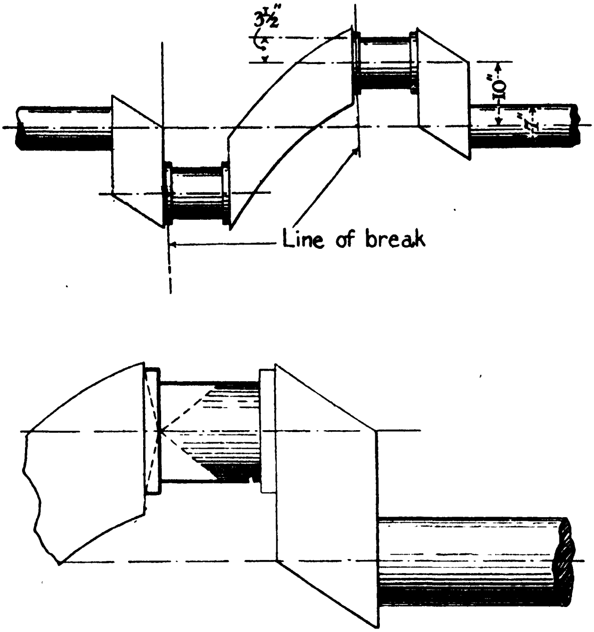


FIG. 72.—CAST STEEL CRANKSHAFT BROKEN OFF BETWEEN THE WEB AND REPAIRED BY THE ELECTRIC-ARC WELDING PROCESS. Dotted Line represents the Ends prepared for Welding.

Fractures in furnace or shell plating must be cut clean out to the full section of the plating, V-eed as already described and welded up by commencing at the bottom of the V and working the metal as it is deposited diagonally, each layer crossing the previous layer with its grain at an opposite angle. It is most important to train welders from the very commencement to get their metal right through the section of the plating. When the weld is completed, the metal added should be chipped, so that the section of the plating through the weld is only a very little in excess of that of the original plate.

Fractured or worn stern frames, rudder posts, stem posts, wastage on stern and other hull plating can be most successfully made good by the metallic arc process. Figs. 78A–D, 79, and 80 illustrate one of many stern frames repaired by the writer's company recently. The repair was carried out to the entire satisfaction of the Admiralty, Board of Trade, and superintendents. The photographs are self-explanatory.

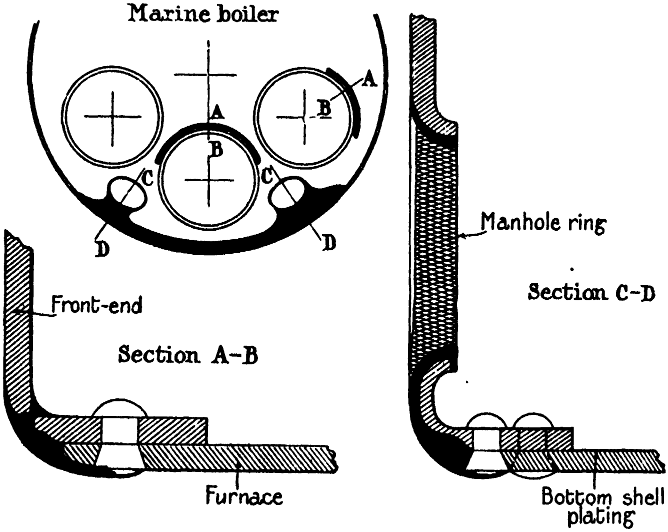


FIG. 73. MARINE BOILER: EXTERNAL REPAIRS.

Many remarkable repairs to machinery have also been carried out in marine and land installations.

The repairs effected by arc welding on several interned German and Austrian vessels in New York in 1916 were of supreme interest, and are splendid examples of what can be done.

A number of excellent articles have already appeared in the leading engineering magazines descriptive of these repairs, which will be referred to in the appendix to these articles.

THE FOLLOWING FIGURES (74A, 74B, 74C, 74D, 74E), SHOW VARIOUS WELDS IN CONNECTION WITH WORK ON LAND AND MARINE BOILERS.

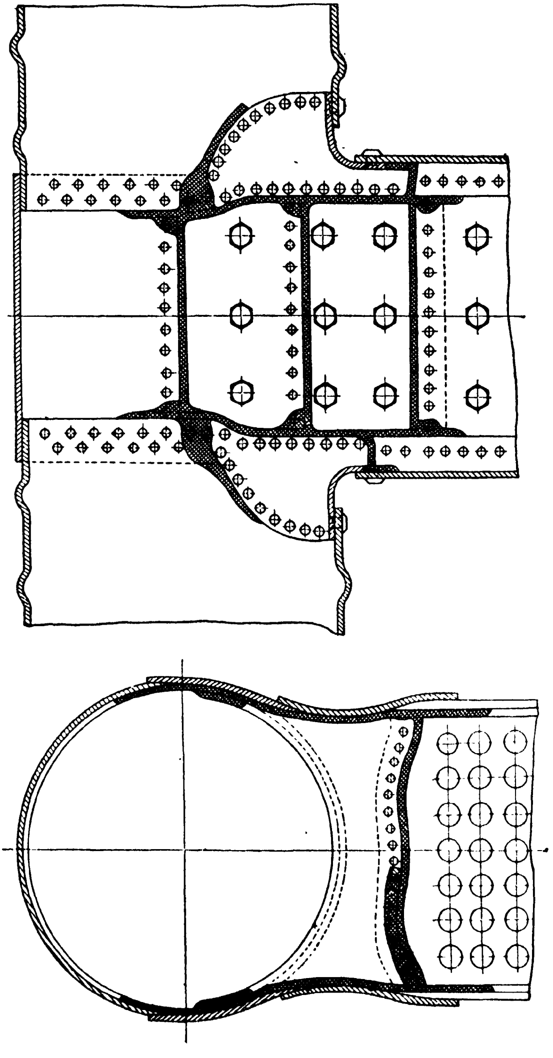


FIG. 74A. MARINE BOILER : COMBUSTION CHAMBER REPAIRS.

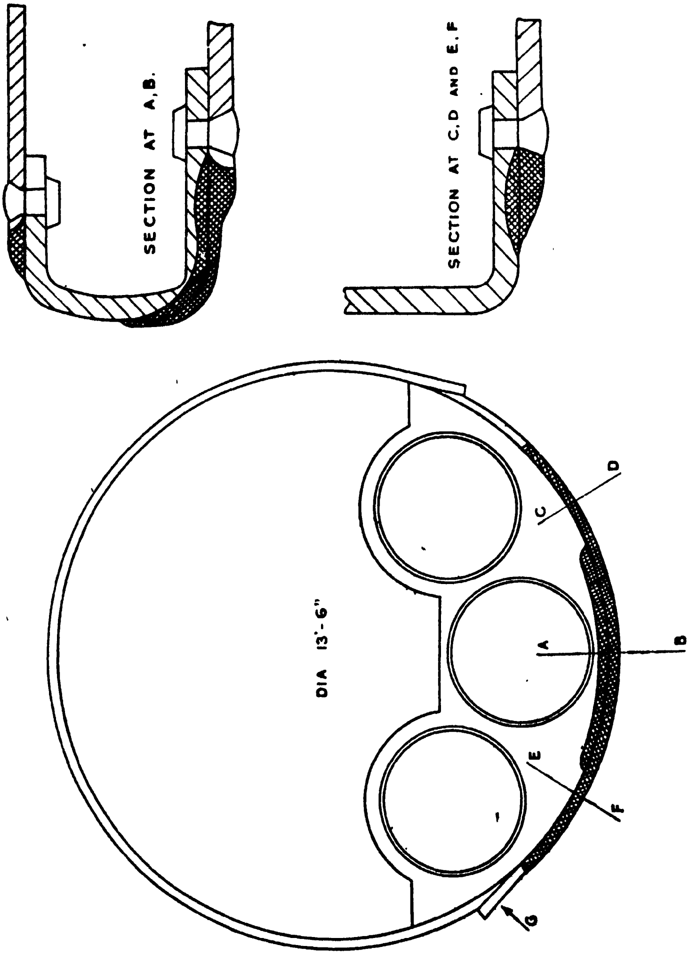


FIG. 74B. MARINE BOILER REPAIRS.

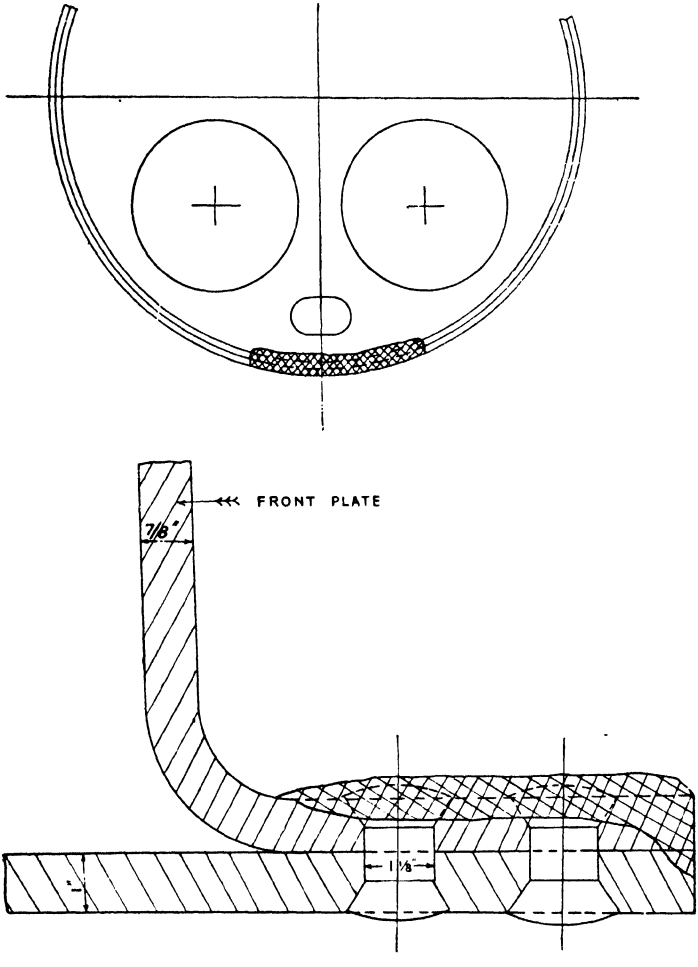


FIG. 74C. MARINE BOILER REPAIRS.

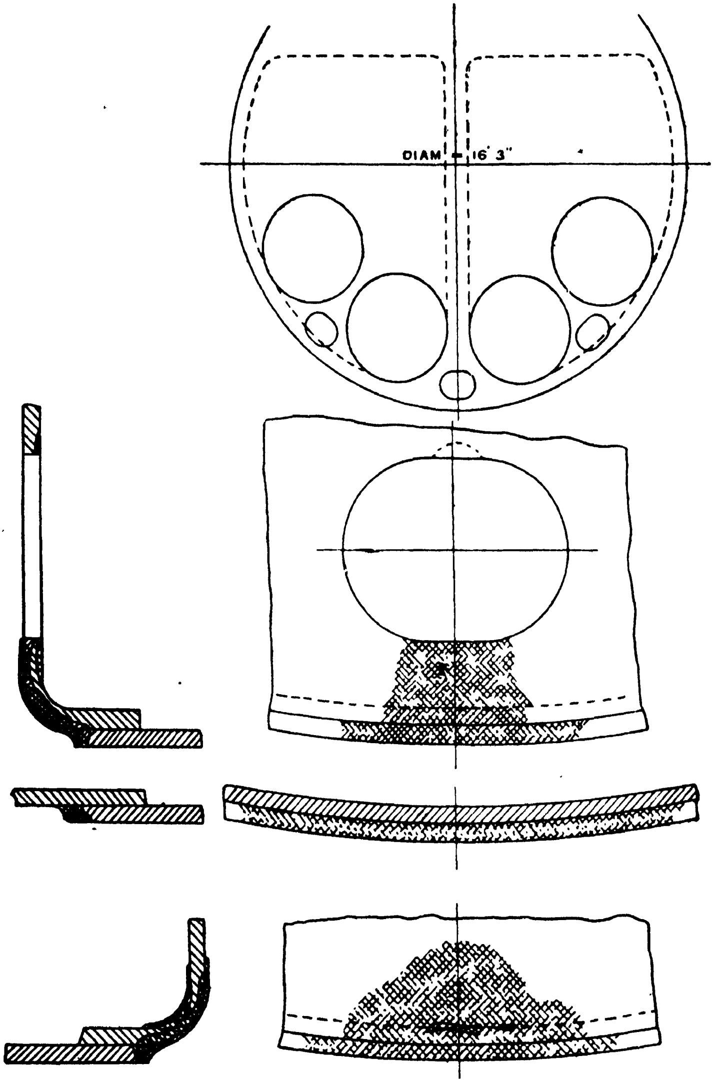


FIG. 74D. MARINE BOILER REPAIRS.

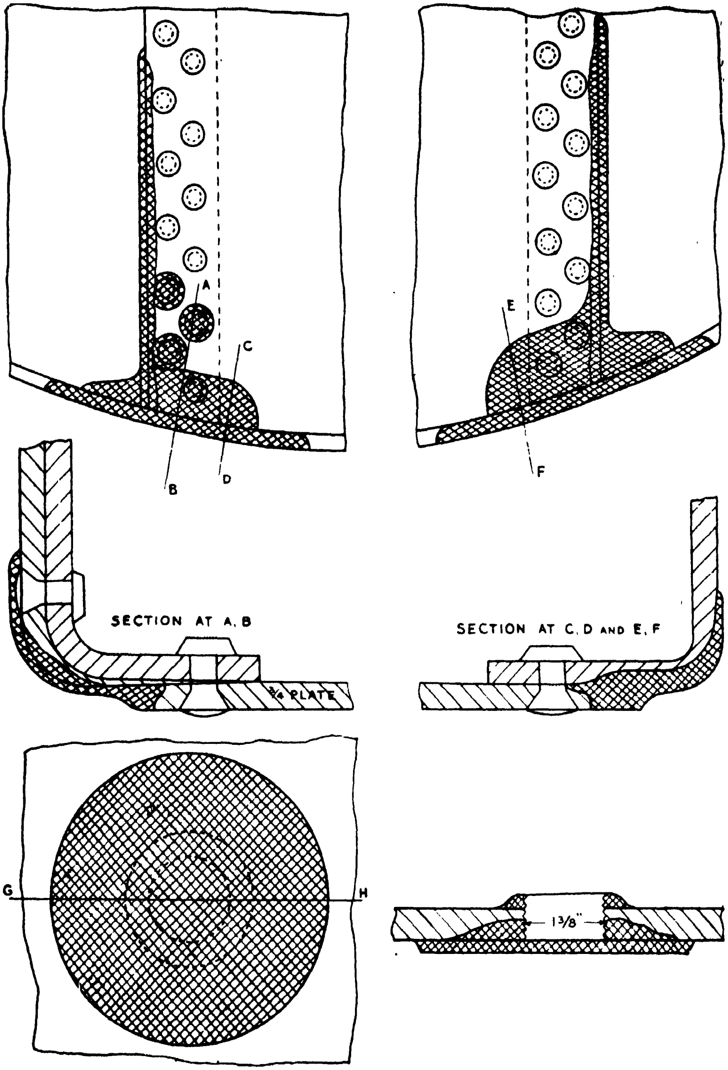
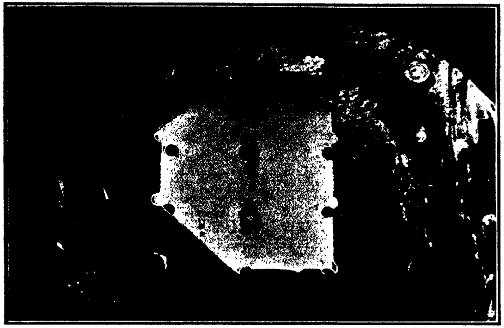
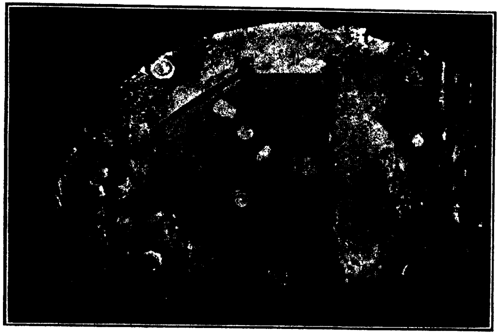


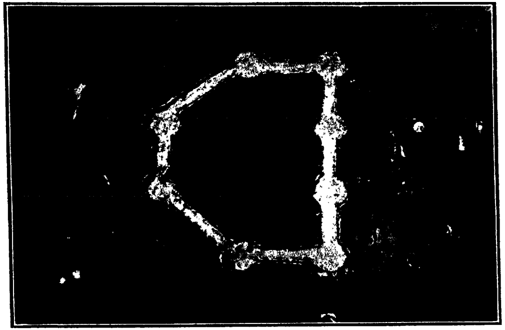
FIG. 74E. MARINE BOILER REPAIRS.



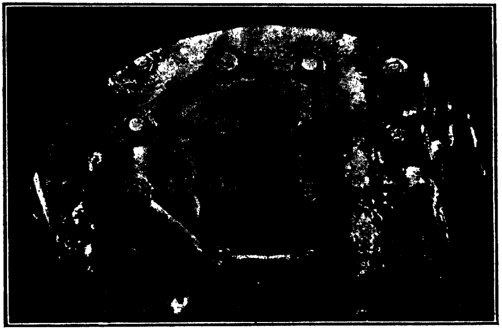
(1) DEFECTIVE PART OF BACK, CUT OUT AND EXISTING PART PAIRED.



(2) NEW PLATE FITTED IN PLACE FOR WELDING.



(3) BUTT OF PLATE AND STAY HOLES WELDED.



(4) HOLES DRILLED, STAYS FITTED AND FINISHED OFF.

FIG. 75A.—STEAM TRAWLER BOILER 6 MONTHS OLD—COLLAPSED COMBUSTION CHAMBER BACK, PRESSURE 180lbs.

In passing, however, the writer would point out that, wonderful as these repairs were thought to be at the time, and cleverly executed they certainly were, yet in this country, for several years prior to 1916, numerous repairs to cast-iron cylinders, bed plates, condensers, pumps, &c., had been most successfully effected in marine and land practice.

FIG. 75B.—REPAIRS BY ELECTRIC ARC WELDING EFFECTED IN 1918, BRISTOL CHANNEL AREA.

Showing a portion of a combustion-chamber back plate cut out and a new plate welded in flush, also part of wrapper side renewed and welded.

The writer has superintended the carrying out of electric welding repairs to cast-iron structures on ships in situ, saving tens of thousands of pounds in the cost of dismantling and renewals. The tube plate landings of condensers when wasted away to the extent that the condenser can only be condemned are now commonly built up completely by means of the metallic arc process. Fractures in cylinders, condensers and pump chambers can also be made good.

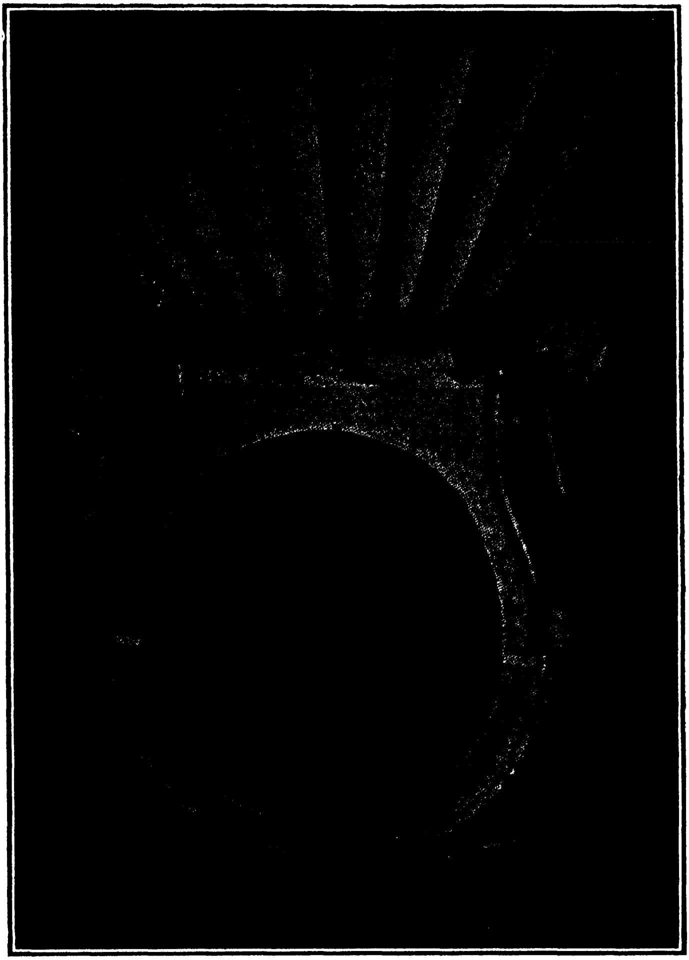


FIG. 76.—REPAIR RECENTLY CARRIED OUT IN LONDON.
New lower half tube plate welded in, in two halves.

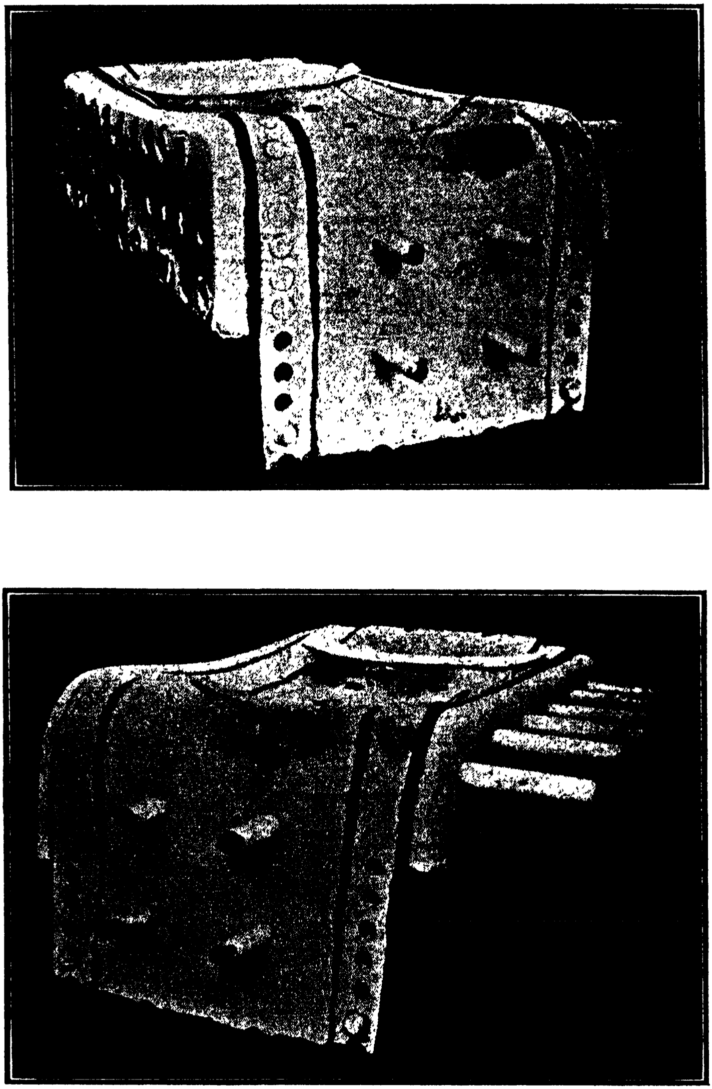


FIG. 77. REPAIR RECENTLY CARRIED OUT ON THE TYNE.
Fractured and collapsed main boiler combustion chamber top cut out, renewed, and electrically welded into position.

hydraulic pressure could be applied prove that the percentage of leaks in the case of machine welds were considerably less than when hand welded.

However, contrasted against these advantages it will be seen that, although in the case of machine welding the cost per foot of weld almost equals that of hand welding, in the latter case the number of feet welded per hour is very much greater, consequently, in the former cases the number of feet of electrode deposited per hour is less, the power consumed is less,

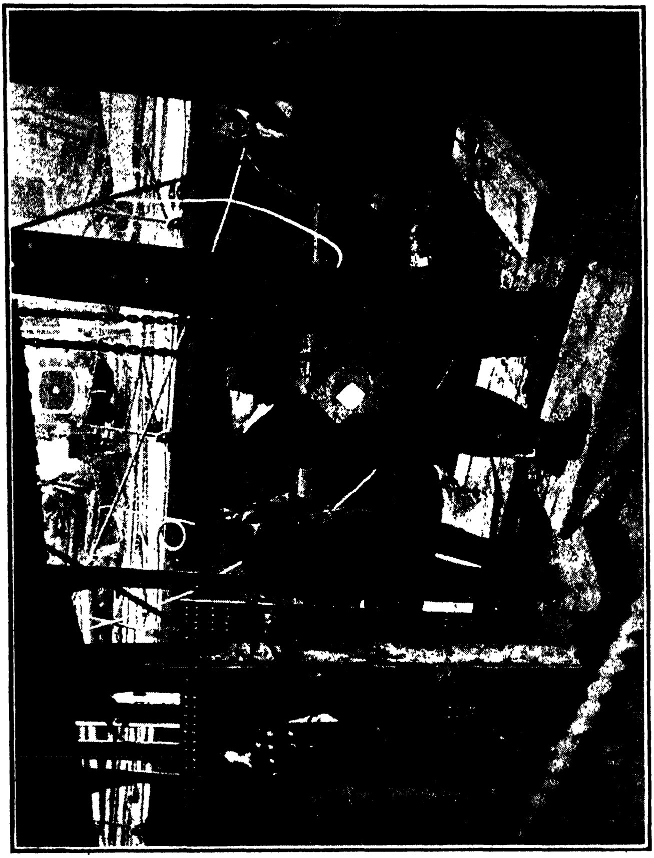


FIG. 79.—LARGE BARGE VESSEL, FRACTURED STEM BAR, CUT OUT AND IN PROCESS OF BEING WELDED UP.

TABLE 5.—*Speed of Welding for Different Thicknesses of Metal.*

Method of welding.	Form of joint.	Thickness of plate.	Energy consumed.		Speed of welding feet per hour.	Electrodes.		Feet of electrodes desposited. Per ft. of weld.
			Volts.	Amps.		Size S.W.G.	Length consumed.	
Machine	Butt straight	0.120	100/110	50/60	25.50	12	42.1 ft.	1.65
Machine	Butt circular	0.120	100/110	50/60	15.90	12	37.5 ft.	2.38
Hand	Butt straight	0.120	100/110	90/95	57.50	12	90.0 ft.	1.56
Hand	Butt circular	0.120	100/110	90/95	36.40	12	51.3 ft.	1.42
Hand 1st layer	V. straight	0.315	100/110	100/110	55.00	10	80.0 ft.	1.45
Hand 1st layer	V. circular	0.315	100/110	100/110	40.60	10	51.2 ft.	1.20
Hand 2nd layer	V. straight and circular	0.315	100/110	130/140	12.25	8	33.0 ft.	2.69

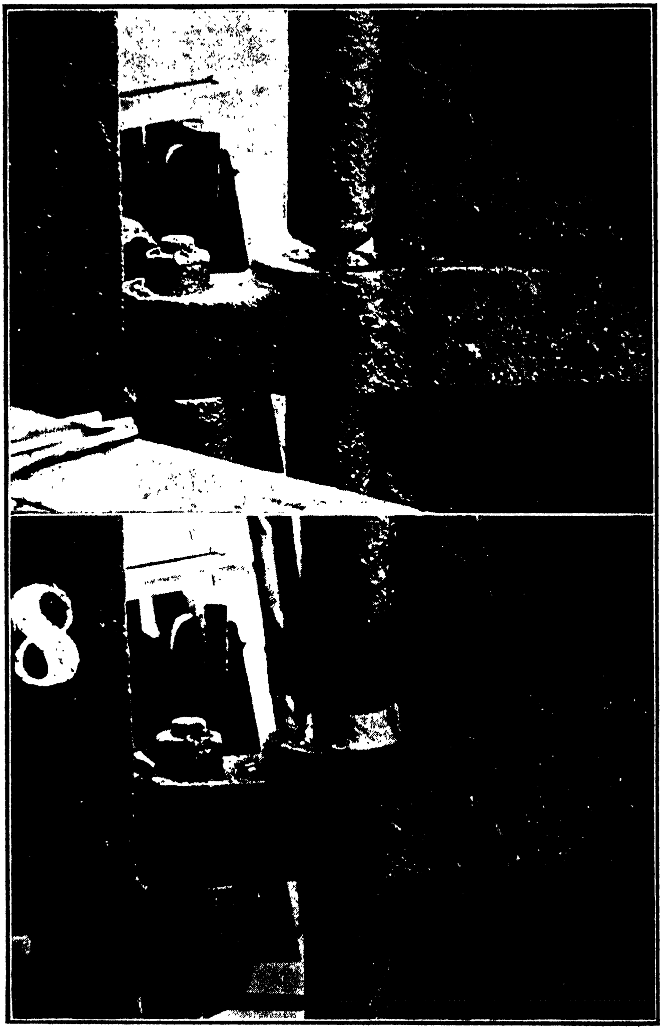
TABLE 6.—*Piecework Price Paid for Welding, Approximate Time taken, and Cost of Electrodes.*

Method of welding.	Form of joint.	Thickness of plate.	Size of electrode.	Length & form of weld.	Piecework price.	Approx. time.	Length of electrode consumed	Price per ft of electrode.
Machine	Butt	0.120	No. 12 S.W.G.	11.5 straight	1.5d.	2.25 min.	19″	1.275d.
Machine	Butt	0.120	No. 12 S.W.G.	25.5 circular	2.0d.	8 min.	60″	1.275d.
Hand	Butt	0.120	No. 12 S.W.G.	11.5 straight	1.2d.	1 min.	18″	1.275d.
Hand	Butt	0.120	No. 12 S.W.G.	25.5 circular	2.5d.	3.5 min.	36″	1.275d.
Hand	V. 1st layer	0.315	No. 10 S.W.G.	16.5 straight	1.5d.	1.5 min.	24″	1.581d.
Hand	V. 1st layer	0.315	No. 10 S.W.G.	28.5 circular	2.5d.	3.5 min.	36″	1.581d.
Hand	V. 2nd layer	0.315	No. 8 S.W.G.	73.5 straight & circular	13d.	30 min.	198″	2.193d.

TABLE 7.—*Feet of Weld per Unit of Power and Approximate Cost Based on Tables 5 and 6.*

Method of welding.	Size of electrode.	Kilowatt hours.	No. of ft. welded.	Cost at say 1d. per un.	Welder's wages.	Cost of electrodes.	Total cost.		
							Per hour.	Per ft. of weld.	
					s. d.	s. d.	s. d.		
Hand	No. 12 S.W.G.	9.660	57.50	9.660d.	6 0	9 6	16 4	3.4d.	
Hand	No. 10 S.W.G. 1st layer	11.025	55.00	11.025d.	5 0	10 6	16 5	3.58d.	12.76d.
Hand	No. 8 S.W.G. 2nd layer	14.175	12.25	14.175d.	2 2	6 0	9 4	9.18d.	
Machine* ...	No. 12 S.W.G.	5.775	25.50	5.775d.	3 4	4 5	8 3	3.5d.	
Machine* ...	No. 12 S.W.G.	5.775	15.90	5.775d.	1 3	3 11	5 8	4.3d.	

* Does not include Power for Machine. *See* Section on Comparative Costs.



IG. 80.—"CARGO STEAMER" RUDDER POST 6″ DIA., BROKEN AT SECOND ARM, CUT OUT, WELDED AND DRESSED OFF.

and the total cost per hour is less. Thus, the output per hour in the former case is considerably less than with hand welding.

Nevertheless, it is quite within the range of possibility that the machines could be speeded up in several directions, and still turn out reliable work.

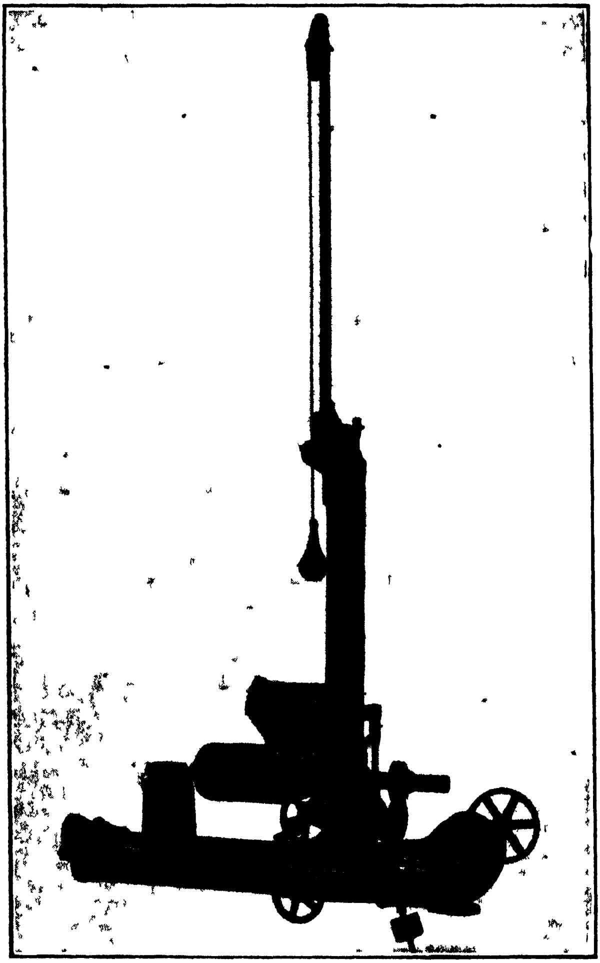


FIG. 81.—SEMI-AUTOMATIC ARC WELDING MACHINE.

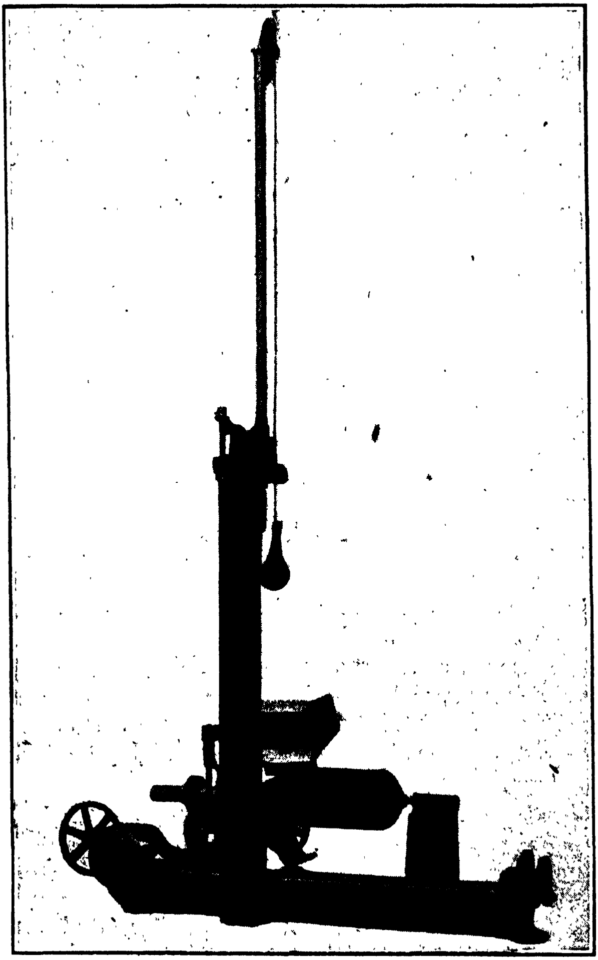


FIG. 82.—ANOTHER VIEW OF FIG. 81.

CHAPTER IX.

TESTING AND STRENGTH OF WELDS.

THE question is sometimes asked: Can welding be correctly tested to give results of any practical value to an engineer?

The subject is a very broad and complex one. In the great majority of cases where welding is performed, the line of weld cannot be tested, and consequently there always remains the element of chance whether the repair is efficient, and will stand up to its work or fail immediately work is put upon it, or give out after a short working endurance.

For this very reason engineers in the past have been, and, indeed, a large number to-day are, suspicious of welding when the result of a failure would entail serious or costly consequences.

This attitude is not surprising when it is considered that the past record of the application of welding, taking all methods into account, has been anything but reassuring. Moreover, the technique and science of welding has been, and in the majority of cases even to-day is, little understood.

In the case of gas welding and smith's welding, the army of so-called experts has grown to a surprising figure, yet out of this huge number of professional welders in this country the writer could not pick out 1 per cent. who could prove that they were really experts and understood thoroughly the technique of their profession.

Electric arc welding suffers much in the same way, but has the additional guarantee of average efficiency in that the equipment is far too expensive in first cost and maintenance for the individual craftsman to set up on his own, and hence arc welding is mostly carried out by a company and under the supervision of trained engineers.

Nevertheless, even under these conditions, it is seldom found that the operators are fully trained and periodically tested to ensure that their work is uniform and of the highest quality.

The process of arc welding, given well-designed machinery, pure materials and expert training, is to a very great extent a more mechanical and fool-proof operation than either of its contemporary systems, yet the influence of the human element is clearly shown from results in Table 8. Each of the welds was carried out by different operators, but as exactly as possible under equal conditions of working.

The operators who made the above welds were considered good welders, though the results of the test pieces were anything but satisfactory except No. X1, see Table 8, which broke beyond the line of weld.

Tables 9 and 10 show what can be obtained by arc welding, and are not record results, being average results obtained by operators in the writer's firm, and which form a standard of proficiency. No operator is allowed to touch important work until he can maintain this standard of competency.

Thirty-one specimens were cut off the same plate, and 30 cut into two equal halves, each 9 in. long, scarfed and welded by the metallic arc process. The unwelded specimen was tested against the welded specimens. The results for the carbon welds were obtained in the same manner. The 30 welded specimens in each case were divided into two lots of 15, the better results in one lot, and the poorest results in the other lot. The average result was then taken of each 15, and recorded as the extreme latitude which would be allowed to a welder as a proof of his proficiency.

Before proceeding further with the question of testing of welds it will, perhaps, be advisable to briefly enumerate the principal defects to which a weld is usually prone.

COMMON DEFECTS IN WELDS.

Penetration.—One of the most prevalent defects is that of lack of penetration. This occurs in all classes of welds, and is usually caused by trying to weld with insufficient power behind the arc, by using too low a current density to properly fuse together the added electrode or filling metal and the work. On the other hand, it may be the result of not keeping the electrode (metallic) down to the work and allowing the metal to be deposited in granular form, which will cover portions of the work which is not at a fusion point.

The result is twofold. The strength of the weld is very considerably reduced and that portion of the work not properly welded constitutes a vulnerable point at which the weld will first commence to tear, and will quickly extend. Again, the bending and fatigue resisting properties of the welded joint will fall to a low figure.

These defects can be avoided by choosing the correct size of electrode or diameter of filling rod, regulating the current density to suit the electrode and the work according to the heat conductivity of the work being welded as explained in a previous section, and keeping the end of the electrode just in the molten surface and feeding down at a uniform rate.

Adhesion.—The defect of adhesion is generally produced by welding with too low a current density, or a too heavy electrode for the section of the metal in the pieces being joined. The former case deposits the metal in a too vicious form, with the result that slag or foreign matter present cannot rise to the surface as the weld proceeds, and consequently gets imprisoned in the molten bath.

TABLE 8.—*Mild Steel Specimens Welded with No.* 10 *S.W.G. Gauge Electrode.* 90 *Amperes.* 60 *Volts.*

Mark on specimen..	Unwelded	X1	X2	X3	X4	X5
Dimensions in inches	1.482	0.706	1.1	1.09	1.17	1.19
Yield. Tons per sq.in.	15.52	1.700	15.5	17.02	14.75	14.28
Max. load per sq. inch	25.44	26.400	23.3	19.68	18.75	16.70
Elongation per cent..	32.5	—	4.9	3.25	3.60	2.70

TABLE 9.—*Mechanical Tests on Boiler Steel Plates Welded by the Metallic Arc Process.*

Mark on specimen	Unwelded	(.)	(..)
Original dimensions on line of weld	(A) 2.0×0.51 (B) 2.0×0.51 (C) 2.0×0.51	2.05×0.511 2.00×0.565 2.01×0.510	2.05×0.5111 2.05×0.5411 2.01×0.516
Original cross-section where fracture occurred	1.02	1.10	1.10
Yield—			
Total load tons........	16.80	20.45	..
Stress tons pr. sq. inch	16.47	18.61	..
Maximum load—			
Total tons	27.71	28.375	32.549
Stress tons per sq. inch	27.17	25.795	29.59
Contraction of area,p.cent.	46.30	15.03	51.6
Elongation on 8 in.	2.52	1.74	2.13
,, p.c. in orig. lgth...	30.05	18.40	24.60

TABLE 10.—*Mechanical Tests on Mild Steel Specimens Welded by the Benardos Arc Process.*

Mark on specimen	Unwelded	X	XX
Original dimensions on line of weld	(A) 2.9 × 0.509 (B) 2.9 × 0.511 (C) 2.9 × 0.511	2.02 × 0.50 2.03 × 0.54 2.03 × 0.51	2.01 × 0.51 2.00 × 0.565 2.01 × 0.561
Original cross sect. where fracture occurred	1.482	1.09	1.13
Yield—			
Total load, tons	23.00	18.55	15.80
Stress, tons per sq. in.	15.52	17.02	13.98
Maximum load—			
Total tons	37.70	21.45	23.76
Stress, tons per sq. in...	25.44	19.68	21.03
Contraction of area, p.c...	29.76	12.00	12.73
Elongation on 8 in.	2.60	0.276	0.451
,, ,, p.c. in orig. lgth	31.25	4.15	7.00

Even if the current density is correctly chosen, adhesion may be caused by careless workmanship, by building up the weld too quickly, and by failure to keep the bath of metal in the weld perfectly free from dirt and slag.

GAS AND AIR BUBBLES.

We have already warned the would-be welder against troubles likely to accrue through the absorption of gas in a weld. Molten metal at the welding temperature readily absorbs gas, and hence the welder must be most careful to protect his bath of metal from the surrounding air and from gases formed during the process of welding. The point of the electrode should be kept well down to the molten metal, and fed in at a uniform and continuous rate. Each time the arc is broken and restruck, a bubble of gas tends to form, and during the interval of stoppage gas is liable to be absorbed by the hot metal, unless well protected, and tends to escape during the process of solidification, but often becomes trapped, due to the fact that the top layers solidify first.

Air bubbles in a weld very considerably affect the ultimate strength of the weld and its power to resist fatigue and vibration.

The finish of a weld is a very fair guide to determining an operator's skill without actually testing his work; for if the finish of his work is good, then very probably the interior is likewise. There are welds which are insufficiently filled. The added metal has not penetrated right through if it is a V-eed joint or a fracture; consequently the section of effective metal at the line of weld is less than the original section, with resulting decrease in strength.

FINISHING OFF WELDS.

Weldsare sometimes hollow, or have valleys and peaks; this is generally the result of using too high a current density and the bath of molten metal has been too mobile.

A neat finish of a weld can be usually obtained by the judicious use of a light hammer while the metal is still at a red heat; but hammering should never be applied once the metal has cooled below a dull red heat.

In the case of copper and certain of its alloys, this latter precaution need not necessarily apply.

It is a good practice to briskly hammer up the weld as it proceeds. This is a most effective treatment, it increases the fatigue resisting properties of the material and gives the metal a more fibrous nature and consequently increases its tenacity. However, it has the effect on metal at a black heat of causing brittleness.

If resort is had to annealing to relieve possible internal strains set up during welding, it is worth noting that reheating above 800°F. has a detrimental effect.

Now, one must bear in mind that the majority of the defects which we have outlined are hidden in the body of the weld, and the welder himself is often ignorant of their presence. The operator therefore requires to know whether his welds are good, bad or indifferent, so that he can estimate his attempts, correct his faults, and gradually train himself up to the high state of efficiency which it is possible to obtain with the electric arc process.

In practice, of course, it is not usual, or, indeed, even practicable, to break the joint in order to measure its strength or examine its internal constitution and appearance. However, the welder can carry out trials on similar metals to those he has to work on, and submit these test pieces to the various tests.

It should be the care of the superintendent to periodically submit specimen welds of individual welders to the standard machine tests for tenacity and elongation, etc., and to encourage healthy competition amongst the operators by exhibiting the best results, and, if possible, to offer some inducement to encourage each welder to attain results above the maximum yet obtained.

SIMPLE METHODS OF TESTING.

The welder himself, or his foreman, can judge fairly accurately the quality of welds by three simple methods. Corrosion, hammering, and bending.

The micrographic test or corrosion test can be applied to all metals, providing the specimen to be tested is not less than $\frac{3}{16}$ in. in thickness.

This simple test is very interesting and instructive. The welded specimen is cut in half along the line perpendicular to the line of welding. The section through the weld is then highly polished. This is done by filing the cut section with a rough file, and after with a smooth file, and finally with a dead smooth file, then obtaining a high polish by means of very fine emery cloth.

All traces of grease and finger marks must be strictly avoided, and immediately the polishing is complete paint the surface with any suitable etching liquid. It will be found that the structure of the weld will immediately develop, and the corrosive action will be complete in a few minutes, when the surface should be quickly but thoroughly washed in running water and dried with methylated spirits, and finally painted with pure clean varnish to preserve the test piece.

The success of this test depends upon a high and uniform polish and absolute freedom from grease ; the rest is simple.

It is, perhaps, curious, but none the less true, that neither the cutting of the part welded nor the polishing discloses any defects ; on the contrary, it gives one the impression that the weld is perfect. However, as soon as the etching liquid is applied the defects begin to show up.

The etching agent first attacks the oxide, exposes any adhesion, blowholes, and eventually discloses the general structure of the weld.

The welder need only examine the test piece to recognize all his defects and can tell whether at the same time he has burned the metal or not.

The etching or corrosive liquids are made up as follows:

For Iron or Steel: Water, 10 parts; potassium iodide, 2 parts; iodine, 1 part.

For Copper, Brass and Bronzes: Water, 75 parts; nitric acid, 25 parts.

For Aluminium and its Alloys: Water, 10 parts; hydrochloric acid, 90 parts.

The hammer test of mild steel welds will indicate the ductility of the weld and the tenacity; according to the size of the specimen, this test can be more or less severe, and might include a drop test.

Hammering pure and simple is, perhaps, of greatest value for welds of copper and brass. After annealing the weld the metal can be beaten out with a hammer, though from time to time re-heating the weld to prevent hardening. If a weld of copper or brass is perfect, it will be possible to hammer down to extreme limits of thinness without showing cracks.

The bending tests as a rule confirm the tensile tests as regards the ductility of the metal, and hence welders should frequently apply a bending test to samples of their work.

In all cases the added metal should be in the fold of the bend, so that if there is a lack of penetration in the weld the defect will soon be exposed.

The specimen is best bent by means of a steady pressure rather than by shocks, and the angle at which the weld begins to crack should be noted. A sound weld should enable the piece to be bent right over and back again without fracture.

In order to test the relative values of riveted, electrically arc welded and acetylene welded joints, a set of samples were

TABLE 11.—*Mechanical Tests on Riveted, Arc Welded and Acetylene Welded Joints.*

Samples and preparation.	Breaking strain.	Length after breaking.	Per cent. efficiency.
	In lbs.		
Original piece of steel plate	58,600	8.80 in.	97.66
Lap joint, electric arc welded ..	54,800	8.94 in.	91.33
Lap joint, riveted and welded .	54,200	9.22 in.	90.33
Butt joint, electric arc welded .	47,800	8.28 in.	79.66
Butt joint, acetylene welded ..	36,800	8.23 in.	61.33
Lap joint, riveted only	35,00	..	58.33

Nominal strength of the steel plates was 60,000 lb. per the square inch.

made up and tested, with the results shown in Table 11. The pieces of steel were $\frac{3}{8}$ in. thick, 8 in. long in the straight section. The welds were made by an operator of average skill only, and therefore the comparisons are true commercial tests.

In practice the joints welded are more often than not reinforced, and consequently an efficiency of over 100 per cent. can easily be obtained.

All welding, in so far as possible, should be tested before being put into service, especially where there is any risk to human life. Fortunately, in actual practice this can be and is carried out, for instance, in steam boilers, air compressors, and any receptical which has to hold pressure. The hydraulic test of $1\frac{1}{2}$ to $2\frac{1}{2}$ normal working pressure when possible to apply is a very safe and satisfactory manner of proving the efficiency of the welding.

However, in such a case as welding of ships' shell plating and general constructional work it is difficult to apply any test of any real value. If the outer surface of the welding is briskly hammered to remove any surface skin, and paraffin washed over its inner surface, any porosity will be soon indicated. Hence, in important work of this kind, only operators thoroughly well trained and eminently reliable should be employed.

CHAPTER X.

GENERAL CONSIDERATIONS IN ARC WELDING.

THE advent of the great war gave a tremendous impetus to electric arc welding, due largely to the vast quantities of munitions required. For rapid production of munitions welding was soon found to fill the gap in manufacturing processes right well, and authorities turned their close attention to improving and applying arc welding to many industrial requirements where hitherto electric welding had not been thought possible or quite inadequate.

The great success achieved in this field has been the cause of calling the attention of many high authorities to the great possibilities of the application of the process of arc welding to ship construction.

Major James Caldwell, R.N., and his staff were untiring in their efforts to introduce arc welding wherever by its application production could be speeded up. Their efforts have already met with unprecedented success, and a vast amount of splendid work has been done under their initial direction.

LLOYD'S OFFICIAL TESTS.

Lloyd's Register of Shipping have now formulated rules regulating the acceptance of arc welding in ship construction, and a schedule of requirements of welders and systems applied to ensure at all times that the workmanship is good and the materials used and system of application are sound and reliable, thus, as it were, protecting the public, the consumer and the welding industry.

It may be of interest to record here that several cross-channel barges have been constructed and launched in which rivetting was entirely eliminated and replaced by electric welding.

So far as the author is aware, these barges have proved eminently successful, and give promise of great and immediate extension in the use of arc welding in the fabrication and construction of large ships.

A comprehensive series of tests on electrically arc welded joints have now been completed, under the direction of Prof. W. S. Abell, of Lloyds' Registry. The objective of these tests was to determine the relative strength of electrically arc welded and rivetted joints and their respective ability to resist the alternating stresses to which ships are subject.

The results are very satisfactory and are of considerable interest and importance. The results of these official tests agree in the main with those obtained by the author from time to time, and even better results have been obtained than those shown by Prof. W. S. Abell.

To describe in detail how these and the Author's tests were carried out, and to tabulate all the figures obtained, would require a treatise of considerable bulk. With apologies, therefore, the writer proposes to set out briefly the conclusions officially confirmed.

TABLE 12.—*Elastic Limit for Electrically Welded Specimens.*

	Plain plate.		Longitudinal weld.		Transverse weld.	
Thickness	½"	¾"	½"	¾"	½"	¾"
Elastic limit in tons per square inch ...	15.0	15.1	18.2	16.4	16.2	14.6

To determine the modulus of elasticity of the material actually forming the weld, specimens were prepared by building up test bars entirely of electro-deposited metal. The author has found the average value to be in the region of 11,620 tons per square inch. Prof. Abell puts the figure somewhat higher—namely, 11,700 tons per square inch. Prof. Abell also gives the value for wrought iron at 12,500 tons and 13,500 tons for mild steel.

It is now evident that up to the elastic limit the extension in the region of the weld is practically coincident with other portions of the plate, but at stresses beyond the elastic limit the ductility of the weld falls considerably below that of the unwelded portion of the plate. The elongation in 8 in. of a welded specimen only averaging about 12 per cent. against 25 to 30 per cent. for mild steel.

Electrically welded butt joints compare in tensile strength very favourably with solid plating. For mild steel plating welded with ordinary commercial metal electrodes the strength of the welded joint varies from 90 to 97 per cent. of the tensile strength of the unwelded plate, and can, by reinforcing, be well above 100 per cent.

Lap welded joints welded with a full fillet along one caulking edge and a single run of weld on the other edge give an ultimate strength compared with the unwelded material of 70 to 85 per cent. A riveted lap joint treble riveted gives 65 to 70 per cent. of the strength of the unperforated plate.

ALTERNATING STRESSES.

It is very important to know the behaviour of welded joints under the influence of alternating stresses. For example, ships, and indeed many parts of machinery, are subject to alternating stresses.

For rotating specimens* it is found that a welded bar will withstand not less than 62 per cent. of stress that an unwelded bar can withstand when subjected to a large number of repetitions of alternating stress, while for stationary welded plates subject to alternating stress the figure is higher, being in the nature of 70 per cent.

A lap welded plate can withstand over 60 per cent. of the number of repetitions of alternating stress necessary to fracture a treble riveted lap joint.

Welded plates can withstand an impact or a crushing strain practically as well as an unwelded plate. This is a useful characteristic in ship constructional work, as a vessel is liable to receive damage from heavy weather.

SOME CONCEPTIONS OF ARC PHENOMENA.

In order to obtain uniform and consistent welding under widely different conditions of operation, it will be necessary to have a very much more accurate and a broader knowledge of what actually is happening when a weld is made by means of an electric arc, and the laws governing that operation.

The problems presented by all welding are particularly

---

* *Application of Electric Welding to Large Structures.* By Prof. W. S. Abell, "Proceedings of Institute of Civil Engineers, 1918–19."

within the province for solution of the engineer, the chemist, and the metallurgist. So far as present investigation carries us, the engineer has paid the most attention to the subject, and, indeed, has almost come to the limit of his powers to develop the process further along scientific lines. The chemist and the metallurgist, on the other hand, have only touched the fringe of investigation.

The engineer has perfected machinery for carrying out arc welding operations, has thoroughly investigated what can be accomplished with our present knowledge, pointed out the successes and limitations of the processes and pointed out a profitable line of development. The problems are now ripe for solution by the chemist and the metallurgist.

Without doubt, the understanding of and adherence to a few fairly obvious and fundamental requirements will result, not only in good and consistent welding, but will facilitate successful and economical operation of the various systems. It is often wise, moreover, to appreciate the limitations of a system and to be able to judge of the advisability of its application, having regard to the requirements of the finished product.

CHARACTERISTICS OF METALLIC ARC FUSION.

When the arc is struck with the metal electrode, this arc is found to have a highly luminous centre core of iron vapour, surrounded by a flame most probably entirely consisting of gaseous oxides. Simultaneously chemical combinations occur, due to the extremely high temperature prevailing in the arc stream, and at the positive and negative poles between the vaporized metals and the atmospheric gases.

These reactions continue until the arc core is completely enveloped by a flame of incandescent gaseous compounds.

Now, as a result of the high temperature of these vapours, assisted by local air currents, draughts are created which tend to remove this protecting screen round the arc core as rapidly as it is formed. Thus the welder has to manipulate his electrode so as to continually secure the maximum protection of the arc flame and the deposited metal. This protection can fortunately be secured by maintaining a short $\frac{1}{8}''$–$\frac{3}{16}''$ length of arc as far as possible unbroken, and the proper inclination of the electrode to compensate for draught currents.

Figs. 83 and 84 are interesting. They show sections taken through deposits formed with a short (20 volt) and a long (35 volt) arc. Fig. 84 shows the corresponding surface views of the deposited metal.

Comparing Fig. 83 with Fig. 84, it will be seen that there is a distinct superiority in fusion, concentration, and economy of deposited electrode, freedom from porosity, and reduction in area of thermal disturbance by the use of the short arc. It is impossible adequately to control the long arc flame, and in consequence to protect the deposited metal from oxidation. Fig. 85, on the right, shows excessive porosity, due to the introduction of oxide and blow holes.

Porosity results usually, as we have previously explained, from frequent striking and interrupting of the arc.

It may be here said that a short arc can be maintained with a high or low potential system. With the former systems less skill is required, and possibly a better continuity of arc circuit is obtained.

Certainly, on a low potential system, a greater degree of skill is required to maintain a steady, continuous arc; but when this skill has been acquired the operator is compelled to keep a short arc. A reactance coil in series with the arc circuit considerably facilitates the maintaining of a uniform and continuous arc, while at the same time it very materially assists in keeping the current in the arc constant, and levels up the current and voltage peaks. The effect of reactance in the arc circuit is clearly indicated by reference to Fig. 86.

It is clearly necessary as far as possible to keep the current in the arc circuit maintained at a reasonably constant value, because the rate of fusion is a function of the current and for all practical purposes is independent of the arc voltage.

FACTORS INFLUENCING FUSION.

The fusion obtained at the surface and in the body of the metal is very largely determined by the scarf angle, arc current, arc length, as well as by diameter of electrode used.

Sections through welds are seen in Fig. 87. The right-hand specimen was scarfed to an angle of 60 deg., and the two

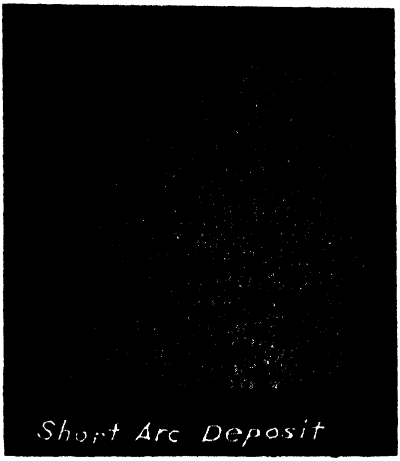


FIG. 83.

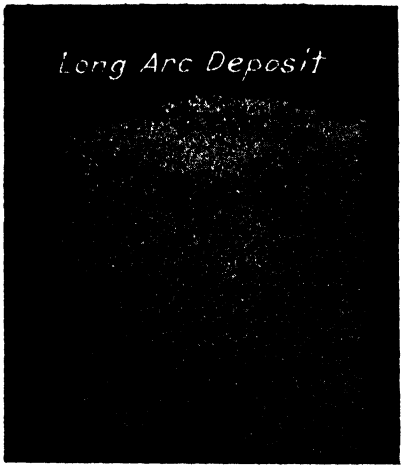


FIG. 84.

SECTIONS TAKEN THROUGH DEPOSITS FORMED WITH A SHORT AND A LONG ARC.

halves practically abutted. As a result, as can be seen, the bottom of the weld proved to be inaccessible to the welder; arc contact was uncertain, and the surface merely covered by molten metal formed above. By separating the parts to be joined ⅛ of an inch and scarfing to 90 deg. satisfactory fusion was obtained, shown by the weld on the left of Fig. 87.

We have already given tables showing the effect of diameter of electrodes and value of current on different sections of plating.

FIG. 85.—SURFACE VIEWS OF DEPOSITED METALS.
(*See* FIGS. 83 AND 84.)

It has often been asked whether the shank of the metal welded is affected by the heat of the arc during the time occupied in completing the weld, and to what extent is this influence detrimental to the original plate.

The author has, in order to ascertain the extent of the effect of the applied heat, as well as to examine the micro-structure of the weld, made from time to time a series of micro-photographs of the juncture of the original and the added metal, to show the changes which take place in the structure of the material.

We know now from close and repeated examination of these photographs that the original material is only disturbed by

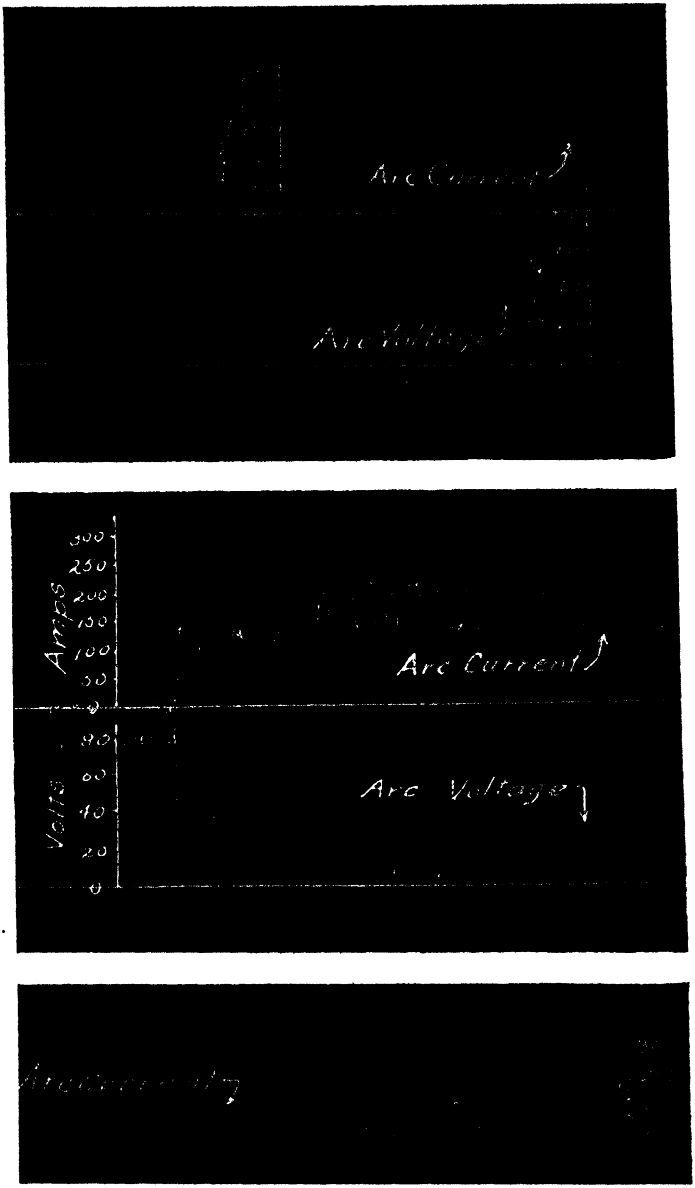


FIG. 86.—OSCILLOGRAMS SHOWING THE EFFECT OF REACTANCE IN THE ARC CIRCUITON A FIXED POTENTIAL SYSTEM.

the heat to a total extent of about $\frac{1}{16}$ of an inch. Indeed, in thin plates, this distance of disturbance is much less. In a good weld there is little or no evidence of oxidation. A perfect juncture is obtained between the plate and the added welding material. The material in the weld has the appearance of being almost pure iron.

TABLE 13.—*Chemical Analysis of Metallic Electrodes used in Arc Welding and the Metal Deposited in the Weld after Passing through the Arc.*

Type of electrode.	Composition.				
Special flux coatings	C.	Mn.	Si.	S.	P.
Original mild steel plate ..	0.160	0.500	0.025	0.034	0.028
Quasi arc A.	0.091	0.46	..	0.021	0.050
Deposit	0.03	0.021	0.058	0.037	0.038
Double arc	0.085	0.35	..	0.054	0.108
Deposit	0.045	0.068	0.045	0.035	0.056
Equipment and engineering	0.115	0.505	..	0.081	0.0162
Deposit	0.065	0.15	0.036	0.056	0.100
Scott Anderson	0.057	0.32	..	0.026	0.014
Deposit	0.084	0.07	0.039	0.06	0.333
Jones	0.224	0.25	0.001	0.026	0.024
Deposit	0.052	0.17	0.029	0.046	0.038
Quasi arc B.	0.136	0.350	0.110	0.030	0.015
Deposit	0.030	0.037	0.020	0.031	0.02
Quasi arc C.	0.123	0.58	0.045	0.46	0.006
Deposit	0.053	0.19	0.039	0.048	0.04
Special coated	0.048	0.008	0.065	0.010	0.082
Deposit	0.046	0.04	0.031	0.033	0.066
Bare Electrodes :					
Original mild steel plate ..	0.125	0.563	0.041	0.061	0.043
Roebling	0.16	0.56	0.016	0.024	0.032
Deposit	0.05	0.18	0.011	0.036	0.031
Norway iron	0.049	0.021	0.08	0.007	0.025
Deposit	0.049	0.018	0.011	0.015	0.020
Swedish iron.............	0.05	0.16	..	trace	0 05
Deposit	0.042	0.14	..	0.003	0.041
Cold rolled steel	0.11	0.72	0.011	0.123	0.087
Deposit	0.05	0.11	0.011	0.072	0.086
Hot rolled steel	0.17	0.50	0.011	0.045	0.012
Deposit	0.14	0.14	0.011	0.039	0.012

Chemical analysis of the deposited metal seems to confirm this latter observation. In Table 13 analysis of a few characteristic electrodes is given, as well as the metal deposited after passing through the arc. As a whole, the action is one of refining of the iron. The action of the atmospheric gases appears to refine the vaporized metal, decreasing particularly the carbon and manganese constituents.

Some deposits show a slight increase in deposits of sulphur and phosphorus and silicon. This may be attributed to their absorption by the hot filler metal from the shank metal. The inclusion of sulphur and phosphorus is to be regretted as the resultant weld is made hard and brittle in consequence.

A very close examination of the micro-photographs of the weld metal has frequently disclosed short straight lines, which indicate the presence of nitrogen; and a careful chemical examination has proven nitrogen to be present to an amount which, though not very large absolutely, is yet 10 times as great as in the solid plate.

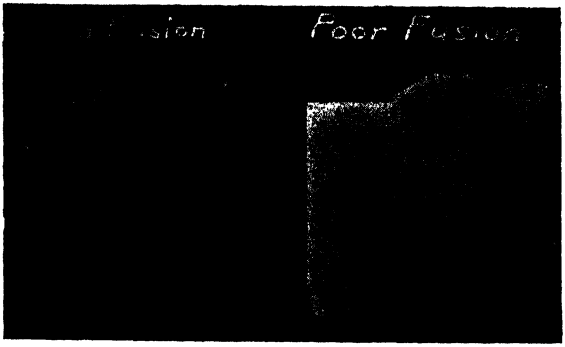


FIG. 87.—CROSS-SECTION THROUGH FUSED METAL, SHOWING SHANK METAL AND FUSED METAL HALF-WAY THROUGH WELD.

NOTE.—The shank metal is seen to the left and the deposited metal to the right in each photograph. Good fusion is shown in the left-hand photograph and poor fusion in the right-hand one.

Nitrogen has the effect of rendering steel strong with respect to tensile strength, but brittle.

This inclusion of nitrogen in the weld is very difficult to prevent, yet, strange to say, the fact of its presence and influence has almost been entirely lost sight of, and little or no real investigation as yet has been made upon this point. The author is of opinion that the matter is worthy of very close examination, which might result in some valuable knowledge.

CHAPTER XI.

ECONOMICS OF ELECTRIC ARC WELDING.

FUTURE INVESTIGATION.

THERE has now opened up a wide field of investigation work upon the economics and technique of electric welding, and in particular electric arc welding.

Firstly, then, there is the question of nitrogen and its effects, as we have already mentioned.

Again, we have stated that the deposited weld metal appears to be pure iron; but is it pure iron? The physical and mechanical properties are in reality considerably removed from those of pure iron, and the metal cannot be said to behave as pure iron. Where, then, lies the difference? Possibly this difference can be explained by saying that you cannot take work out of any material where it has not in some way first been put into that material. Wrought iron or mild steel certainly has work put into it before applying it to engineering use, but the deposited metal in the weld has not, as a rule, any mechanical energy stored up.

If a weld is well hammered and annealed it certainly exhibits improved qualities mechanically and physically. However, the author is of opinion that the last word has not by any means been said upon this point.

Then there is the vexed question of protective coverings for metal electrodes to adequately protect the fused metal and the deposited electrode metal. In this country most authorities up to now have been strongly in favour of the refractory slag covered electrodes. This system is quite good, but the writer ventures to say that it is totally unnecessary and very expensive. What is the alternative? In America very considerable success has been attained with the bare metal electrode. The average results obtained by a trained operator agree very closely in respect of mechanical tests with the average results obtained with specially coated electrodes given an equally trained welder. One is forced, therefore, to ask where is the great advantage of specially coated electrodes, and whether these slight advantages warrant the considerably greater expense in the production and use of the latter?

It is claimed that it requires greater skill to obtain with the bare electrode a thoroughly satisfactory weld than is required to obtain an equally good weld with coated electrodes; and, moreover, a weld made with a coated electrode has higher fatigue resisting properties than one made with bare electrodes.

The author is not at all convinced that these claims have been conclusively proved. At all events, the improvements in mechanical properties, if any, of the coated electrode and the reliability of welds made by the average operator, compared with the difference in results obtained with either system under the influence of the human element, leads one to the conclusion that the whole matter requires careful and scientific investigation.

It has been contended that the coating round the electrode can be made the vehicle of constituents which will give desired characteristics to the added metal.

The author ventures to state emphatically that no external covering of the electrode, whether in the nature of a refractory liquid flux, or a gaseous flux-forming substance, can in any way influence the chemical or physical state of the weld apart from protecting the metals in fusion from the surrounding atmospheric gases.

The constituents intended to alloy with the deposited metal are on the wrong side of the arc.

Considerable experimental work with alloy steel electrodes have further persuaded the author of the truth of this latter statement. Research work is now going forward upon metal electrodes for a higher class of weld than ordinary mild steel.

The Alloy Welding Process, Ltd., and the British Arc Welding Company, Ltd., have already completed some valuable work in this connection, and hope shortly to produce materials suitable for welding 50-ton steels.

It must be admitted that in the present state of our knowledge the results obtained with any system of arc welding to a very considerable extent depend upon the skill of the individual operator.

The best results that the author has yet seen were obtained by the British Arc Welding Company, Ltd., who use an electrode covered with a thin sleeve of flux, which under the heat of the arc forms a protecting atmosphere of inert gases. Their expert operators produce uniform welds in the nature of 32 tons tensile strength per square inch.

TABLE 14.—*Electric Welding.* (*Metallic Electrode System*).
Speed and Cost of Working.

These figures were obtained from a series of tests carried out under the supervision of Major James Caldwell, of the Welding and Labour Section, at the Admiralty. They were made indoors under good working conditions, and allowances should be made where conditions are not likely to be good and the work not easy of access.

Thickness of plate.	Feet per hour.	Units per foot-run at 1d.	Electrodes per foot-run.	Labour at 1s. per hour.	Total cost per foot.
$\frac{1}{16}''$	28.0	0.07	1.25	0.43	1.75
$\frac{1}{8}''$	30.0	0.18	1.4	0.4	1.9
$\frac{3}{16}''$	24.0	0.27	1.8	0.5	2.5
$\frac{1}{14}''$	22.0	0.45	2.0	0.54	3.0
$\frac{5}{16}''$	10.0	0.73	4.0	1.2	5.9
$\frac{3}{8}''$	7.5	1.6	5.5	1.6	8.8
$\frac{7}{16}''$	6.0	2.0	8.0	2.0	12.0
$\frac{1}{2}''$	5.0	2.4	9.6	2.4	14.4

The polarity of the electrode has a marked effect upon the mechanical strength of the weld. Unless the work to be welded is very fine, or has a low fusion temperature, the metal electrode should be negative in polarity; furthermore, overhead operation is decidedly easier of accomplishment with the electrode negative.

SPEED AND COSTS OF WELDING.

It is exceedingly difficult—and is, in fact, impossible—to make any absolute statements in connection with costs and speeds on account of the many variables involved.

However, a fair idea of the comparative costs and speed of welding for the oxy-acetylene and the electric arc systems may be gathered from results of records taken of each process under as near as possible equal conditions, such as conditions of operation, thickness and form of material welded, position of work, each based on average prices for labour, materials and generation of gasses per cubic foot and electrical power per kilowatt-hour.

TABLE 15.—*Electric Welding (Benardos Arc System). Speed and Cost of Working.*

Thickness of plate.	Length. of weld.	Time.	K.W.H. at per hr.	Labour at 1s. per hr.	Filling in metal.	Carbon used at 4d. ft.	Feet per hour.	Total cost per ft. run.
$\frac{1}{16}''$	12"	2 mins. 50 secs.	0.7d.	0.57d.	0.08d.	0.05d.	21.0	1.4d.
$\frac{1}{8}''$	12"	2 ,, 45 ,,	0.8d.	0.54d.	0.08d.	0.05d.	22.0	1.4d.
$\frac{3}{16}''$	12"	4 ,, 5 ,,	1.25d.	0.85d.	0.15d.	0.10d.	14.0	2.3d.
$\frac{1}{4}''$	12"	5 ,, 2 ,,	1.5d.	1.0d.	0.3d.	0.12d.	12.0	2.9d.
$\frac{5}{16}''$	12"	7 ,, 10 ,,	2.1d.	1.4d.	0.45d.	0.15d.	8.3	4.1d.
$\frac{3}{8}''$	12"	10 ,, 55 ,,	3.1d.	2.1d.	0.6d.	0.2d.	5.5	6.0d.
$\frac{7}{16}''$	12"	14 ,, 5 ,,	4.2d.	2.7d.	0.9d.	0.3d.	4.2	8.1d.
$\frac{1}{2}''$	12"	17 ,, 0 ,,	5.0d.	3.4d.	1.2d.	0.4d.	3.5	10.0d.

Figures were obtained from actual tests. Time given is total time, and includes swaging of weld after welding. Time during which current is used is approximately 50 per cent. of total time for weld.

TABLE 16.—*Welding by Oxy-Acetylene. Speed and Cost of Working.*

Thickness.	Length.	Oxy used.	Acetylene used.	Cost oxy.	Cost acetylene.	Cost filling wire.	Time taken.		Cost labour at 1s. hr.	Feet per hour.	Total cost.
							Min.	Sec.			
$\frac{1}{16}''$	12"	0.44	0.34	0.2d.	0.34d.	0.12d.	3	—	0.1d.	16.0	1¾d.
$\frac{1}{8}''$	12"	0.74	0.57	0.32d.	0.51d.	0.45d.	4	55	0.1d.	12.2	2½d.
$\frac{3}{16}''$	12"	1.4	1.0	0.72d.	0.9d.	0.45d.	5	20	1.6d.	11.0	3.1d.
$\frac{1}{4}''$	12"	3.2	2.46	1.6d.	2.2d.	0.5d.	8	20	1.6d.	7.5	5.9d.
$\frac{5}{16}''$	12"	5.6	4.3	2.8d.	3.8d.	0.9d.	9	37	1.9d.	6.2	9.4d.
$\frac{3}{8}''$	12"	7.14	5.5	3.57d.	4.5fd.	1.2d.	12	15	2.4d.	4.9	11.6d.
$\frac{7}{16}''$	12"	9.3	7.1	4.65d.	6.39d.	1.5d.	15	55	3.2d.	3.77	15.7d.
$\frac{1}{2}''$	12"	11.5	8.8	5.75d.	7.92d.	1.5d.	—	20	2.87d.	4.18	18.0d.

Oxygen at 4s. 6d. per 100 cubic ft., Carbide at 4d. per lb. equals 9d. per cubic foot. Filling wire at 0.04d. per foot, $\frac{1}{16}''$; filling wire at 0.15d. per foot, $\frac{1}{8}''$; filling wire at 0.3d. per foot, $\frac{3}{16}''$.

For miscellaneous repair work accurate costs cannot be given, but the comparison under standard conditions will still more or less hold good.

It may be here said that as the mass of work to be welded increases, and the accessibility of the work decreases, also, while the conditions of operation become less favourable, such as exposure to the open air, line of weld vertical, or above the operator, opposition of work to free expansion and contraction, or near presence of rivets, studs, etc., the figures for cost and speed become more favourable to electric arc welding.

Tables 14, 15, and 16 show the speed and cost of butt welding steel plates varying in thickness from $\frac{1}{16}$ in. to $\frac{1}{2}$ in.

It will be observed from Table 15 that the cost per foot-run decreases in proportion to the increase in section of the metal welded; the same applies in a less degree with the metallic arc system (Table 14). In actual practice on heavy repair work this proportionate decrease in cost exists to a very much greater extent, owing to the heavy standing charges which are more or less constant bearing a smaller proportion to the total cost.

In oxy-acetylene welding this condition of affairs can generally be said to be the reverse. From Table 16 it will be seen that the proportionate cost increases with the increase of section of the material welded. The consumption of oxygen and acetylene gas rapidly increases as the section of weld increases. This is due to the greater power of the work being welded to conduct away the heat being applied to it externally to fuse the metals.

In the case of arc welding, the heat is generated internally in the metal itself, and at a rate far beyond that at which the metal can conduct it away from the point being welded. Thus it is easy to see from this consideration alone that arc welding has a very big advantage over its contemporary system.

The cost per foot-run of $\frac{1}{2}$ in. plate is shown to be :

Oxy-acetylene welded	18.0d.
Electric arc (Benardos)	10.0d.
Electric arc (metal electrodes)	14.4d.

In the latter case the cost of the electrodes used should be about half, owing to the fact that in these tests, and also in the tests shown in Tables 5, 6, and 7 in section on "Machine Welding," the electrodes used were specially coated, and were very expensive. (This coating made no appreciable difference to the speed of welding.) Thus the cost per foot-run with the metallic arc system should more nearly approach that given for the Benardos system.

In speed of welding, the electric arc system it will be seen has the advantage. In average practice the Benardos system is far quicker than the metallic electrode system, though, of course, it is not so universally adaptable. In the tests shown in Table 16 the value of the current used was much lower than was possible without detriment to the weld, especially was this so in the case of the $\frac{5}{16}$ in. to $\frac{1}{2}$ in. plate. Thus the speed is shown to be very much lower than is usual and possible.

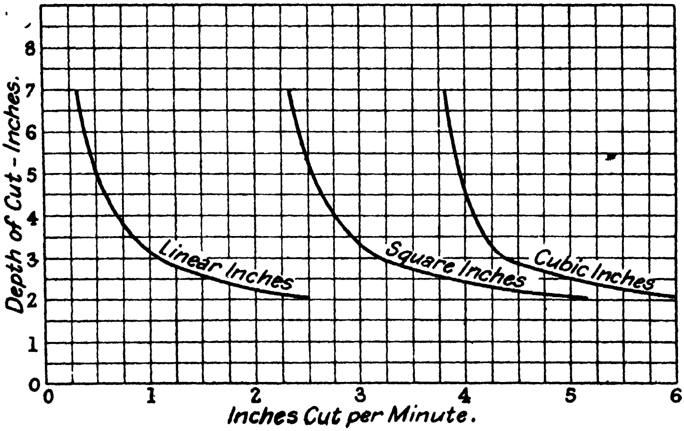


FIG. 88.—RATE OF CUTTING CAST-IRON PLATES (LENGTH OF CUT GREATER THAN DEPTH) WITH 1 IN. DIAMETER CARBON ELECTRODE AT 625-650 AV. AMPS., 45-65 ARC VOLTS (CUT MADE PROGRESSIVELY IN ONE DIRECTION).

To give some idea of the saving to be derived by resorting to electric welding for reclaiming worn or broken parts of machinery, etc., the cost of repair of several of the illustrations as shown in these articles is given in Table 17. It must be borne in mind that the figures given represent the cost to the consumer, and is, therefore, the gross cost plus the repairers' profit, etc. Moreover, the labour charges in the district in which the repairs were carried out were very high.

Before concluding these articles on welding, it may be of interest to briefly refer to

CUTTING OF METALS.

In the field of cutting it must be admitted that the oxy-acetylene flame is pre-eminently the more satisfactory for cutting iron and steel.

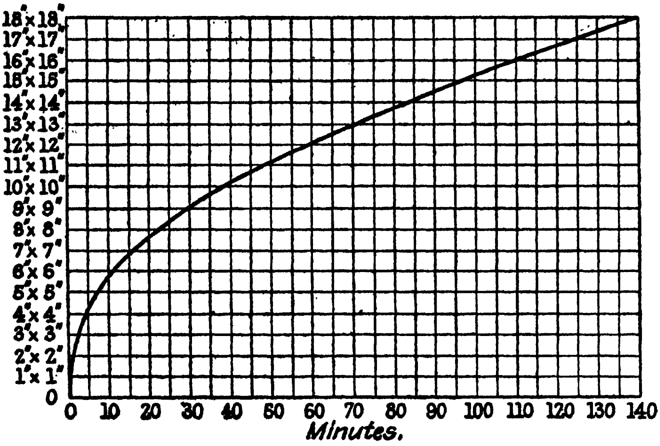


FIG. 89.—RATE OF CUTTING CAST-IRON SQUARE BLOCKS, 1 IN. DIAMETER CARBON ELECTRODE, AT 625-650 AV. AMPS., 45-65 ARC VOLTS. POSITION OF KNEE IS DETERMINED BY ELECTRODE DIAMETER, LENGTH AND CLEARANCE REQUIRED BY OPERATOR WITH GIVEN HOLDER.

The action produced by the gas flame is that of rapid oxidation, with the removal of a minimum amount of material.

The electric arc, on the other hand, does not render such a fine line of cut as with the gas flame, as it virtually burns the metal away.

Table 18 shows a few figures of cutting speeds, using the electric arc for cutting mild steel sections.

The average rate of cutting is thus 0.45 sq. in. per minute per 100 amperes.

Cast iron, however, contains carbon combined with the iron, and in the free state in such large percentages that the gas flame cannot directly burn through. The metal must be actually melted, and therefore the electric arc here more than holds its own, owing to its very great intrinsic heat value.

Figs. 88, 89, and 90 show a series of curves for cutting cast iron by means of the electric arc.

Heavy risers on iron or steel castings can be quickly and cheaply cut away with the arc, and hence, in the foundry, arc generating sets are now finding an ever-extended use.

TABLE 17.—*Giving Approximate Cost to the Consumer of work Illustrated in these Articles. The Cost of Labour varies from 1s. 8d. to 8s. an hour. Allowance must be made, moreover, for Conditions under which Work was carried on.*

Illustration figure	Cost.	Remarks.
49	£0 15 0	Per flange, inclusive of mandling.
52	£4 10 0	Tank 2ft. diameter, 24ft. of weld
52	£3 2 0	Three flanges and two branches and the main joint.
53	£2 15 0	
55	£34 0 0	Diameter of anchor 15 in., cut in two, scarfed, welded, and reinforced.
57	£2 18 0	Half bearing broken away.
58	£2 0 0 to £3 10 0	Annealing covers, approx. 18 ft. of fracture to be cut away and welded up solid.
58	£12 0 0 to £15 0 0	Truck suspension bars.
58	£1 10 0 to £3 15 0	Motor yokes.
58	£0 10 0 to £2 0 0	Fractured cylinder packets, cylinder walls, broken flanges, joints, etc.
59	£0 17 9	Average.
60	£0 10 0 to £1 10 0	Increase in diameter ⅜ in., and key wages filled in.
62 63	£2 0 0 to £2 10 0	Depending on accessibility and extent of fracture.
65	£1 1 0	Average per spoke.
66	£1 7 0	Cut away by carbon arc and new piece fitted and welded in 10 hours 47 minutes.
69	£5 0 0	Average wear.
70	£9 0 0	Per average wear.
71	£7 0 0	Fractures cut out and welded and reinforced.
72	£1 5 0 to £2 10 0	

TABLE 18. *Power Consumption and Cutting Speed in Electric Arc Work.*

Size of section cut in inches.	Area cut, sq. in.	Cutting current in amps.	Cutting time, minutes.	Cross-sec. cut sq. in. per min., per 100 amps.
8.0″ × 8.0″	64.0	810	27.0	1.89
8.0″ × 8.0″	64.0	600	41.75	1.645
8.0″ × 8.0″	64.0	320	98.0	1.31
6.0″ × 6.0″	36.0	810	14.50	1.975
6.0″ × 6.0″	36.0	600	21.67	1.78
6.0″ × 6.0″	36.0	320	44.33	1.63
4.0″ × 4.0″	16.0	600	5.62	3.06
4.0″ × 4.0″	16.0	320	10.08	3.226
2.0″ × 4.5″	9.0	600	2.53	3.72
2.0″ × 4.5″	9.0	320	5.05	3.49
1.375″ × 3.25″	4.47	320	2.25	3.99
12.0″ × 1.0″	12.0	400	3.0	1.0
12.0″ × 0.5″	6.0	320	2.17	0.9
1.0″ × 0.375″	0.375	320	1.25	1.15
shaft 8″ diam.		425	50.0	3s. 4d.*

*Cost of current and electrodes.

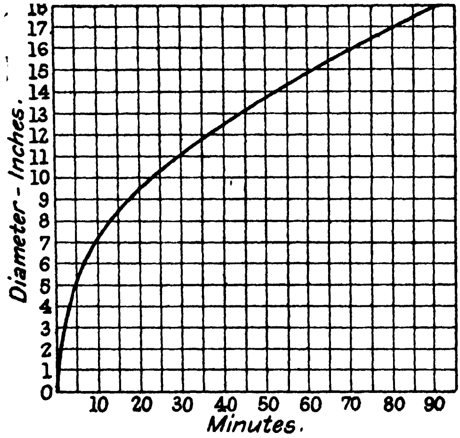


FIG. 90.—RATE OF CUTTING CAST IRON CIRCULAR CROSS-SECTION 1 IN. DIAMETER CARBON ELECTRODE, AT 625-650 AV. AMPS., 45-65 ARC VOLTS.

Very much more could be written upon the subject of electric welding; however, the author ventures to hope that these few notes on the various systems and their application will find a place in the interest of engineers generally, and that some suggestions may be gleaned from them that will ultimately lead to profit.

In conclusion, the author wishes to acknowledge with thanks the information and illustrations supplied by interested firms, who very kindly rendered their utmost assistance.

TECHNICAL PAPERS ON WELDING.

"Spot and Seam Welding." "Machinery," March, 1917, pp. 609–13.

"The Welding of Steel Castings," by J. F. Springer. "Rail Loco. Eng.," vol. xxiii., 5, pp. 142–3.

"Autogenous Welding at Albuquerque," by H. L. Hahn. "Rail Mech. Eng.," vol. xciii., 5, pp. 271–2. Seven figs. (Burned or cracked sheets and tubes repaired by gas or electric welding. Welding of flue beads.)

"Modern Welding and Cutting," by E. Viall. "Amer. Mach.," vol. l., 8, pp. 341–6. (iii.—Thermit welding crankshafts, mill pinions, etc. Specific directions for applying the principles of fusion welding. Replacing teeth in large pinions, rudder stocks and the like.)

"Advantages of Spot Welding," by G. A. Hughes and R. H. Pool. "Elect. Weld.," vol. cxxiii., 15, pp. 734–5. Five figs. (Effectiveness of spot welding as compared with riveting. Rivets may be driven noiselessly with welding devices.)

"Electric Welding of High-speed Steel and Stellite in Tool Manufacturing," by P. T. Van Bibber. "Amer. Mach.," vol. c., 10, pp. 425–32. (iii.—A practical way to save an enormous amount of high speed or other steel. Shows how new tools may be produced so as to use the high-priced steel only for vital parts.)

"Electric Welding." "Machinery" (Lond.), vol. xiv., 345, pp. 182–4. Eight figs. (Illustrates special types of electric point and seam welding machines. Electric soldering. Strength of electric welds.)

"Electric Welding and Welding Appliances." "Engineer," vol. cxxvii., 3307, pp. 471–3. (Pt. 14—"Strength of Electric Welds.")

"Electric Arc Welding," by F. A. Anderson. "Mech. Eng." (Amer. Soc. Mech. Engin.), vol. xli., 5, pp. 452–4. Eight figs.

"Modern Welding and Cutting," by E. Viall. "American Mach.," vol. l., 8, pp. 431–6.

"Advantages of Spot Welding," by G. A. Hughes. "Elect. Weld," vol. lxxiii., 15, pp. 734–5.

"Electric Welding of High Speed Steel and Steelite in Tool Manufacture," by P. T. Van Bibber. "Amer. Mach.," vol. l., 10, pp. 425–32.

"Electric Welding." "Machinery, Lond.," vol. xiv., 345, pp. 182–4.

"Steamship Repairs by Electric and Autogenous Welding," by A. Scott Younger. "Trans. Inst. of Electrical Engineers and Shipbuilders in Scotland," vol. liii., Feb., 1910.

"Notes on Welding Systems," by James Caldwell. "Trans. Inst. Engineers and Shipbuilders in Scotland," Jan., 1918.

"Electric Welding," by C. B. Auel. International Engineering Congress, Sept., 1915. "Electrician," vol. lxxvi., 1916, pp. 45, 57, 84, 410.

"Electro-Percussive Welding," by Skinner and Chubb. "Electrician," vol. lxxv., pp. 5, 18. 1915.

"Electric Welding in Railway Work." "Electrician," vol. lxviii., pp. 68, 459. 1912.

"Notes on Electric Welding Practice." "Electrician Review," vol. lxxviii., pp. 91, 132, 183, 211. 1916.

"Electric Arc Welding." "Steamship," vol. xxv., 297. 1914.

"Electric Arc Welding." "Syren," vol. lxxvii., 1000. Oct., 1915. By R. S. Kennedy, M.I.M.E., M.Inst.C.E.

"Electric Arc Welding," by Lieut. C. E. McDowell, U.S.A. "Canadian Engineering," Sept., 1915.

"Some Modern Methods of Welding," by T. T. Heaton. Inst. of Mech. Eng. 1914.

"Some Studies of Welding," by E. F. Law, W. H. Merrett, and W. Pollard Digby. "Journal, Iron and Steel Institute," No. 1. 1911.

"Some Notes on Modern Methods of Electric Welding and their Application," by H. S. Marquand. "Proc. Inst. of Electrical Engineers."

"Electric Arc Welding," by H. S. Marquand. "British Westinghouse Gazette," vol. liii., p. 855, June, 1916.

"Application of Electric Arc Welding," by E. S. Tuck. "Electrical Journal," vol. xi., p. 37, Jan., 1914.

"Equipment for Electric Arc Welding," by E. S. Tuck. "Electrical Journal," vol. xi., p. 565, Oct., 1914.

"Electric Percussive Welding," by C. E. Skinner and L. W. Chubb. "Electrical Journal," vol. xi., p. 640, Nov., 1914.

"Electric Arc Welding." "Electrical Journal," vol. v., 1, Jan., 1908.

"Electric Arc Welding." "Electrical Journal," vol. vii., 10. Oct., 1910.

"Boiler and other Repairs by Electric Welding," by R. S. Kennedy, M.I.M.E., M.Inst.C.E., Institute of Marine Engineers. March, 1918.

"Electric Welding: Its Progress and Application," by T. G. McKay, A.M.I.N.A., M.I.M.E., Liverpool Engineering Society. March, 1918.

"Selection and Application of Electric Arc Welding Equipment," by A. M. Candy. "Electrical Journal," vol. xv., 9, Sept., 1918.

"Arc Welding of Mild Steel," by O. H. Eschholz. "Electrical Journal," vol. xv., 7, July 7, 1918.

"Electric Arc Welding: General Elect. Review." "Electrical Journal," vol. xxi., 12, Dec., 1918.

"Electric Welding: A New American Industry," by H. A. Horner. "Proc. Inst. of Elect. Engineers." "Electrical Journal," vol. xxxvii., 10, Oct., 1918.

"The Application of Electric Welding in Ship Construction and Repairs," by John Reney Smith. "Proc. Institution of Civil Engineers," March, 1919.

"Electric Welding," by T. T. Heaton. "Proc. Inst. of Mechanical Engineers," Nov., 1918.

"Electrical Arc Welding," by H. L. Unland. Association of Iron and Steel Elect. Engineers, America. June, 1918.

"Electric Welding Developments in Great Britain and the United States of America." by James Caldwell and Henry Baley Sayers. "Proc. Inst. of Civil Engineers," March, 1919.

"Experiments on the Application of Electric Welding to Large Structures," by Wescott Stile Abell. "Proc. Inst. of Civil Engineers," March, 1919.

ILLUSTRATIONS

TABLES

INDEX

Printed in Great Britain by Jarrold & Sons, Ltd., Norwich.