Prediction and Optimization of Machining Parameters for Minimizing Surface Roughness and Power Consumption during Turning of AISI 1045 Steel

SYNOPSIS

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by

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INTRODUCTION

The 1980s have witnessed a fundamental change in the way governments and development agencies think about environment and development. The two are no longer regarded as mutually exclusive. It has been recognized that a healthy environment is essential for a healthy economy. Energy and materials are the two primary inputs required for the growth of any economy and these are obtained by exploiting the natural resources like fossil fuels and material ores. The industrial sector accounts for about one-half of the world's total energy consumption and the consumption of energy by this sector has almost doubled over the last 60 years (Fang et al., 2011). The consumption of critical raw materials (steel, aluminum, copper, nickel, zinc, wood, *etc*.) for industrial use has increased worldwide. The rapid growth in manufacturing has created many economic, environmental and social problems from global warming to local waste disposal (Sangwan, 2011). There is a strong need, particularly, in emerging and developing economies to improve manufacturing performance so that there is less industrial pollution, and less material & energy consumption. Energy efficiency and product quality have become important benchmarks for assessing any industry. Manufacturing operations account for 37% of global energy demand (Diaz-Elsayed et al., 2015). U.S. manufacturing industry annually consumes 21.1 quadrillion BTU energy (about 21% of total U.S. energy consumption) and generates more than 1.4 billion metric tons of CO_2 emissions (about 26% of total U.S. CO_2 emissions) (Yuan et al., 2012). Machine tools have less than 30% efficiency (He et al., 2012) and more than 99% of the environmental impacts are due to the consumption of electrical energy used by the machine tools in discrete part manufacturing machining processes like turning and milling (Li et al., 2011). Worldwide, machine tool manufacturing is a USD 68.6 billion industry and very few energy assessments have been conducted for discrete manufacturing facilities (Diaz-Elsayed et al., 2015). Sustainability performance of machining processes can be achieved by reducing the power consumption (Camposeco-Negrete, 2013). If the energy consumption is reduced, the environmental impact generated from power production is diminished (Pusavec et al., 2010). However, sustainability performance may be reduced artificially by increasing the surface roughness as lower surface finish requires lesser power and resources to finish the machining. However, this may lead to more rejects, rework and time. Therefore, an optimum combination of power and surface finish is desired for sustainability performance of the machining processes. There is a close interdependence among productivity, quality and power consumption of a machine tool. The surface roughness is widely used index of product quality in terms of various parameters such as aesthetics, corrosion resistance, subsequent processing advantages, tribological considerations, fatigue life improvement, precision fit of critical mating surfaces, *etc*. But the achievement of a predefined surface roughness below certain limit generally increases power consumption exponentially and decreases the productivity. The capability of a machine tool to produce a desired surface roughness with minimum power consumption depends on machining parameters, cutting phenomenon, workpiece properties, cutting tool properties, *etc*. The first step towards reducing the power consumption and surface roughness in machining is to analyze the impact of machining parameters on power consumption and surface roughness.

RESEARCH MOTIVATION

After well known formula relating tool life to cutting speed given by Taylor in 1907, a lot of research on the modelling and optimization of machining parameters for surface roughness, tool wear, forces, *etc.* has been done during last 100 years. However, a little research has been done to optimize the energy efficiency of machine tools. Moreover, in the past, metal cutting operations have been mainly optimized on the basis of economical and technological considerations without the environmental dimension (Yan and Li, 2013). Reduction in power consumption improves the environmental impact of machine tools and manufacturing processes. Machine tools require power during machining, build-up to machining, post machining and idling condition to drive motors and auxiliary equipment. However, the design of a machine tool is based on the peak power requirement during machining of material which is very high as compared to non-peak power requirement of the machine tool. This leads to higher inefficiency of energy in machine tools. The optimization of machining parameters for minimum power requirement is expected to lead not only to the application of lower rated motors, drives and auxiliary equipment, but also power saving during machining, build-up to machining, post machining and idling condition. In addition to the machining parameters, the power requirement during machining also depends upon workpiece properties and cutting tool properties. In this study, the workpiece material is steel and cutting tool material is uncoated tungsten carbide. This combination is the most widely used combination in the industry and any reduction in power consumption is expected to lead to high saving of power in absolute numbers. No doubt, steel is one of the widely researched materials in machining for more than last half a century, but there is a renewed interest in application of steel because of its sustainability – 100% recyclable and almost indefinite life cycle. Energy requirement for steel recycling is less than one third of aluminum recycling. AISI 1045 steel is widely used in different industries (construction, transport, automotive, power, *etc*.).

Process models have often targeted the prediction of fundamental variables such as stresses, strains, strain rate, temperature, *etc.*; but to be useful for industry, these variables must be correlated to performance measures and product quality (accuracy, dimensional tolerances, finish, *etc*.) (Arrazola et al., 2013). Recent review papers on machining show that the most widely machining performances considered by the researchers are surface roughness followed by machining/production cost and material removal rate (Yusup et al., 2012). Recently, the researchers have started to analyze and optimize the power consumption in machining (Aggarwal et al., 2008; Camposeco-Negrete, 2013; Hanafi et al., 2012). Energy savings upto 6-40% can be obtained based on the optimum choice of cutting parameters, tools and the optimum tool path design (Newman et al., 2012). The process planners as well as operators use their experience with the help of data from machining handbooks and tool catalogs to achieve the best possible machining performance. Due to inadequate knowledge and complexity of factors affecting the machining performance, an improper decision may cause energy inefficiency, low product quality and high production cost. These issues motivated for analyzing and improving the performance of machining process for enhancing product quality and minimizing power consumption. This thesis aims at optimizing the surface roughness and power consumption simultaneously during turning of AISI 1045 steel. Optimization of machining parameters through experimentation is not only tedious but costly also, therefore, this thesis presents a predictive mathematical model to optimize the power consumption and surface roughness simultaneously. Predictive modelling can be used as an effective and an alternative method for the experimental studies in machining.

OBJECTIVE OF THE STUDY

The objective of this study is to develop predictive and optimization models for analyzing the influence of machining parameters on (i) surface roughness, (ii) power consumption, and (iii) finally on surface roughness and power consumption simultaneously. The effect of cutting speed, feed and depth of cut will be studied during the turning of AISI 1045 steel using carbide cutting tools. This objective is achieved by:

- Development of predictive and optimization models to determine the optimum machining parameters leading to minimum surface roughness,
- Development of predictive and optimization models to determine the optimum machining parameters leading to minimum power consumption, and
- Development of a multi-objective predictive and optimization model to determine the machining parameters leading to minimum power consumption and surface roughness simultaneously.

Response Surface Methodology (RSM), Support Vector Regression (SVR) and Artificial Neural Networks (ANN) will be used to develop the predictive models. RSM and Genetic Algorithms (GA) will be used to develop optimization models.

METHODOLOGY

The following methodology has been used to achieve the objectives of the study:

- Development of the experimental setup to get the surface roughness and power consumption data: the process parameters and response variables have been selected for the AISI 1045 steel during turning by carbide cutting tools. Experiments have been designed using Design of Experiments (DOE).
- Development of the predictive models for surface roughness using RSM, SVR and ANN. The developed models have been compared using relative error and validated using hypothesis testing. A mathematical formulation has been

developed by using RSM and an optimization model has been developed using GA. The results have been validated using the confirmation experimental tests.

- Development of the predictive models for power consumption using RSM, SVR and ANN. The developed models have been compared using relative error and validated using hypothesis testing. A mathematical formulation has been developed by using RSM and an optimization model has been developed using GA. The results have been validated using the confirmation experimental tests.
- Development of a multi-objective predictive and optimization model to determine the machining parameters leading to minimum surface roughness and power consumption simultaneously. Grey Relational Analysis (GRA) coupled with Principal Component Analysis (PCA) and RSM have been used to determine the best machining parameters for surface roughness and power minimization simultaneously.

SIGNIFICANCE OF THE STUDY

The efficient use of energy and other resources is important to meet the increasing concern about economy and environment. Machine tool is a major consumer of energy and thus it is a potential sector for energy saving. Machining parameters such as cutting speed, feed and depth of cut play a vital role in machining the given workpiece to the required shape and finish. These parameters have a major effect on the tool-life/tool wear, part accuracy, surface roughness, power consumption, *etc*. in addition to time and cost. The judicious selection of these parameters is significant. The selected machining parameters should give the desired quality on the machined surface with the minimum environmental impact. Traditionally, the selection of machining parameters is carried out on the basis of the experience of the machinist or the process planner and reference to the available catalogues and handbooks. Manual selection of machining parameters highlights the problem of variability in experience and judgment among the process planners. In addition to this, the induction of cost intensive Computer Numerical Control (CNC) machines emphasizes effective utilization of these resources using the optimal machining parameters.

This study focuses on development of predictive and optimization models, which eliminate the necessity of extensive experimentation process currently used in industry to understand relationship between machining parameters and performance characteristics. Development of predictive and optimization models is cost effective and accurate prediction of optimum machining parameters leads to minimum surface roughness and power consumption. The predictive capability could also be used for automatic monitoring. With the known boundaries of surface roughness, power consumption and machining conditions, machining could be done with a relatively high rate of success leading to better surface finish and lower power consumption.

RESEARCH CONTRIBUTION

- Experimental investigations on the influence of machining parameters on surface roughness and power consumption.
- Development of RSM, SVR and ANN models for the prediction of surface roughness and power consumption.
- Development of RSM and GA models for the optimization of surface roughness and power consumption.
- Development of a multi-objective predictive model for the minimization of surface roughness and power consumption simultaneously using RSM coupled with GRA and PCA.
- Development of 3D contour and surface plot to provide a range of near-optimal solutions for the power consumption and surface finish. These can be used by the

part programmers and the operators for selecting the machining parameters from the available range on the machine tools.

Predictive modelling and optimization is a complex and re-emerging field of research. The scope of the research work is endless due to large number of variables involved in machining of materials. The effect of machining parameters like tool geometry, tool coatings, coolants, *etc*. on the surface roughness and power consumption has not been studied. Further, the effect of machining parameters on material removal rate can be analyzed. This work can be extended to include the advanced materials like titanium alloys and composites materials.

This study has optimized the power consumption and surface finish simultaneously. However, in practice surface roughness is not taken as a variable of the machining process but a fixed parameter (predefined range by designers). Therefore, future research can be directed at mapping of optimum machining parameters for minimum energy consumption for a range of expected surface finish. The results can also be analyzed using other optimization techniques such as particle swarm optimization, simulated annealing, artificial bee colony, *etc*., and the effectiveness of various optimization techniques can be compared.

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