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A novel approach to predict surface roughness in machining operations using fuzzy set theory

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Abstract

The increase of consumer needs for quality metal cutting related products with more precise tolerances and better product surface roughness has driven the metal cutting industry to continuously improve quality control of metal cutting processes. In this paper, two different approaches are discussed. First, design of experiments (DOE) is used to determine the significant factors and then fuzzy logic approach is presented for the prediction of surface roughness. The data used for the training and checking the fuzzy logic performance is derived from the experiments conducted on a CNC milling machine. In order to obtain better surface roughness, the proper sets of cutting parameters are determined before the process takes place. The factors considered for DOE in the experiment were the depth of cut, feed rate per tooth, cutting speed, tool nose radius, the use of cutting fluid and the three components of the cutting force. Finally the significant factors were used as input factors for fuzzy logic mechanism and surface roughness is predicted with empirical formula developed. Test results show good agreement between the actual process output and the predicted surface roughness.

Keywords: Design of experiments; Fuzzy logic; Surface roughness; End milling; Process control

1. Introduction

Manufacturing has played an ever-increasing role in our lives. Not only are we concerned with how products are produced and delivered to us, but we are also concerned with how well the products are built. Manufacturers around the world continuously seek new and improved methods of product manufacturing to meet the expectations of the consumer. There are many aspects of manufacturing that can be considered when looking for new and improved methods of production. Efforts can be focused on manufacturing systems, manufacturing processes, or manufacturing materials. All of these efforts together transform raw materials into end products. Within the area of manufacturing processes, different processes can be evaluated for their impact on processing time, efficiency of production methods, and quality of finished products.

The quality of finished products is defined by how closely the finished product adheres to the specifications. Surface roughness (R_a) is the most commonly used index to determine surface quality. It is a measure of smoothness for a machined surface. Surface quality is defined and identified by the combination of surface finish, surface texture, and surface roughness. Surface finish and surface roughness express and represent the same characteristic. Surface roughness is defined as the fine irregularities produced on a workpiece by a cutting tool. Surface texture relates to deviations from a nominal surface that forms the pattern of the surface. The terms surface texture, surface finish, and surface roughness are used interchangeably in industry as well as in this paper [1]. Many lifelong attributes of a product are determined by how well the integrity of the surface finish is maintained. Painting or coating adherence, surface reflectivity, and frictional requirements are examples for which the surface roughness may be specified. Defects occur when the surface roughness requirement is not met. Applied surfaces may fail to adhere properly and parts

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may not assemble properly due to excessive frictional components exhibited through poorly machined surfaces.

Numerous factors affect surface roughness in the machining process. While some factors are difficult or impossible to control, some controllable process parameters include feed, cutting speed, tool geometry, and tool setup. Other factors that are harder to control include tool vibration, work-piece and machine vibration, tool wear and degradation, and workpiece and tool material variability [2]. These factors interact to influence the quality of the surface finish produced. When the surface does not meet the specifications, parameters are adjusted and the original or a new workpiece is inserted into the machining center for machining [3]. Depending on the materials, the effect of major variables on the surface roughness changes significantly. For instance, highly ductile materials tend to induce a built-up edge on the tool nose, hence creating degraded surface in terms of roughness. Very brittle materials such as cast iron also create challenging machining conditions due to fractures, which worsens the surface roughness. In the case of aluminum alloys, as the hardness of material increases, the surface roughness tends to improve. However, very hard materials induce vibration during the machining that generates the rough surface finish. Therefore, some widely machined common materials such as medium carbon alloy steel contain the elements that help improve the machinability. Moderately ductile yet hard materials fixed on a rigid machine tool tend to manifest the desirable machining condition, if the cutting tool materials, coolants, chip breakers and major variables are correctly applied. The major variables can be independently controlled to attain the desired surface roughness. For instance, the feed rate is usually set at a slow level to improve the surface roughness. The cutting speed is set at a rather higher level to prevent the built-up edge from occurring on the tool nose. Cutting depth is usually set to be small in order to reduce the machining vibration as well as the resistance or opposing cutting force from the materials. Overall, a combination of slow feed rate, higher cutting speed, and small depth of cut is employed to generate the smooth surface.

In this context, the main idea behind this research is that one should develop techniques to predict the surface roughness of a product before milling to evaluate the robustness of machining parameters for keeping a desired surface roughness and increasing product quality for a given set of cutting conditions, work material, tool insert type and tool geometry. It is also important that the prediction technique be accurate and reliable [4]. This can be achieved with the help of Fuzzy logic and fuzzy inference systems which are proven to be effective techniques for the identification, prediction and control of complex, nonlinear, and vague systems. Fuzzy logic is particularly attractive due to its ability to solve problems in the absence of accurate mathematical models [5]. The overall objective of this research was to develop an algorithm for milling operation that predicts surface roughness with designed set of conditions. Two approaches DOE and Fuzzy Logic were used where the design of experiments (DOE) is an effective approach to optimize the throughput in various manufacturing-related processes. The fractional factorial DOE and statistical analysis of variance (ANOVA) will be used to represent, infer, and screen the milling parameters in order to generate appropriate training data for the fuzzy logic. Furthermore, ANOVA will be used to check the statistical significance of individual milling parameters on the value of the surface roughness. Once the significant factors are determined, these factors will be used as input parameters for Fuzzy Logic and with the help of Fuzzy inference system. IF-THEN rules are framed depending on the operator's experience and knowledge which employs a mode of approximate reasoning that resembles the decision-making process of humans. The behavior of a fuzzy system is easily understood by a human expert as knowledge is expressed by means of intuitive, linguistic rules [6]. A fuzzy system is usually designed by interviewing an expert and formulating their implicit knowledge of the underlying process into a set of linguistic variables and fuzzy rules. For complex control tasks, obtaining the fuzzy knowledge base from an expert often requires a tedious and unreliable trial and error approach. Unlike neural networks, generic fuzzy systems do not require training data as part of their development process. However, several techniques have been proposed to extract fuzzy rules from training data gathered from observations of the operator control strategy [5]. Fuzzy rules and membership functions are build using *fuzzyTECH* 5.5i software from which fuzzy output (surface roughness) is derived. Surface finish of the machined part is the output of the process which is then compared with the experimental data. Minimum error is obtained through numerous experiments or data points. The fuzzy logic model built is capable of predicting the surface finish for a given set of inputs (cutting speed, feed rate, and depth of cut). As such, the machinist may predict the quality of the surface for a given set of working parameters and may also set the process parameters to achieve a certain surface finish. The model is verified experimentally by employing different sets of inputs. This study deals with the experimental results obtained during end milling on 6061 T6 Al.

2. Theoretical background of fuzzy logic and surface roughness

2.1. Fuzzy logic

Fuzzy logic is a basic concept which refers to all theories and technologies that employ fuzzy set. It is basically a multi-valued logic that allows intermediate values to be defined between conventional evaluations like yes/no, true/false, black/white etc. to degrees of truth between 0 and 1 [7]. Fuzzy logic was invented by Professor Zadeh in 1964. The concept of fuzzy logic came from the idea of grade of membership, which became the backbone of fuzzy set theory. Fuzzy logic is the logic of approximate reasoning with traditional precise reasoning as the limiting case [8]. What zadeh means by “the logic of approximate reasoning” is that in many cases “4th digit” accuracy is not crucial to system performance, but rather, what is important is quick approximate judgments, much like how a human would perform. For example, Zadeh wrote that a set of speed measurements grouped around a point on a speed continuum would be lumped