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Optimization of surface roughness and flank wear using the Taguchi method in milling of Hadfield steel with PVD and CVD coated inserts

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ABSTRACT

In this paper, the Taguchi method and regression analysis have been applied to evaluate the machinability of Hadfield steel with PVD TiAlN- and CVD TiCN/Al_2O_3-coated carbide inserts under dry milling conditions. Several experiments were conducted using the L_{18} ($2 \times 3 \times 3$) full-factorial design with a mixed orthogonal array on a CNC vertical machining center. Analysis of variance (ANOVA) was used to determine the effects of the machining parameters on surface roughness and flank wear. The cutting tool, cutting speed and feed rate were selected as machining parameters. The analysis results revealed that the feed rate was the dominant factor affecting surface roughness and cutting speed was the dominant factor affecting flank wear. Linear and quadratic regression analyses were applied to predict the outcomes of the experiment. The predicted values and measured values were very close to each other. Confirmation test results showed that the Taguchi method was very successful in the optimization of machining parameters for minimum surface roughness and flank wear in the milling the Hadfield steel.

1. Introduction

Hadfield steel (austenitic manganese steel) is a very tough and non-magnetic alloy and having excellent wear resistance with high strength and ductility [1]. In recent years, due to its excellent wear resistance properties this steel has been widely used in various engineering applications including excavators, mining equipment, pumping equipment, railways, rolling mill parts for steel factories and wear-resistant components of machining elements. However, the machining of this steel is very difficult due to its extreme hardness, low thermal conductivity and strain hardening behavior. Consequently, greater cutting forces, higher cutting temperatures and wearing are present making the control of dimension precision difficult during machining [2–4].

The technology of cutting tools is rapidly improving and this development is necessary to improve the wear resistance and performance of machining on difficult-to-cut materials. Improvement in performance can be achieved by increasing the strength of the cutting tools in terms of wear resistance [5]. Coating technology is one of most important ways of increasing the machining performance of cutting tools. In recent years, the tendency towards coating technology has increased with the increase of cutting speed and feed rate. Cementite carbide cutting tools are coated using two different methods: physical vapor deposition (PVD) and chemical vapor deposition (CVD). In the last few years, the comparison of PVD and CVD coatings from the point of machining performance has been the subject of much research. In some studies, PVD coatings produced better results from the point of machining performance [6,7]; whereas CVD coatings showed better performance in other studies [8–12]. For this reason, specification of suitable cutting tools and coating types

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becomes important for increasing machining performance and decreasing production costs.

Surface quality is one of the most significant indicators of engineering materials; whereas surface roughness plays an important role in the specification of the surface quality of the produced parts. Good surface roughness provides important improvements in the tribologic characteristics, fatigue strength, corrosion resistance and aesthetic appearance of the product [13–15]. In addition, the surface roughness affects several attributes of machined parts such as friction, wear, and heat transmission [16]. Another point which plays a key role in high-quality and economical production is tool wear. Surface roughness is related to tool wear and is directly affected by it. There are a number of parameters affecting surface roughness and tool wear such as cutting tool material, coating material, cutting speed and feed rate. Obtaining minimum surface roughness and tool wear by the optimization of these parameters is very important from the aspect of cost reduction. For this reason, in recent years, a number of statistical models have been developed for the analysis and optimization of machining parameters such as response surface methodology (RSM), regression techniques, analysis of variance (ANOVA) and the Taguchi method. The Taguchi-based optimization technique has produced a unique and powerful optimization discipline that differs from traditional practices [17].

Mandal et al. [18] applied the Taguchi method and regression analysis to assess machinability of AISI 4340 steel with newly-developed zirconia-toughened alumina ceramic inserts. It has been observed that the depth of cut is a maximum contribution to tool wear. Nalbant et al. [19] used the Taguchi method to determine the optimal cutting parameters for surface roughness in turning. The orthogonal array, the signal-to-noise ratio, and analysis of variance were employed to study the performance characteristics in turning operations of AISI 1030 steel bars using TiN-coated tools. Experimental results were provided to illustrate the effectiveness of this approach. Ghani et al. [20] applied the Taguchi method to optimize cutting parameters in end milling when machining hardened AISI H13 steel with TiN-coated P10 carbide insert tools under semi-finishing and finishing conditions of high-speed cutting. An orthogonal array, signal-to-noise ratio and Pareto analysis of variance were employed to analyze the effect of the milling parameters. The analysis of the results showed that the optimal combination for a low-resultant cutting force and a good surface finish was a high cutting speed, low feed rate and low depth of cut. Fetecau and Stan [16] investigated the turning of polytetrafluoroethylene composites using a polycrystalline diamond tool in order to analyze the effects of the cutting parameters and insert radius on the cutting force and surface roughness. The signal-to-noise ratio and the analysis of variance were applied to the experimental data in order to determine the effect of the process variables on the surface roughness and cutting force, and predictive models were derived. Statistical results indicate that the cutting force and surface roughness are significantly influenced by the feed rate. Yang et al. [21] applied the designs-of-experiments (DOE) approach to optimize the parameters of a computer numerical control (CNC) in end milling for high-purity graphite under dry machining. The feed rate was found to be the most significant factor affecting the groove difference and the roughness average in the end milling process for high-purity graphite. Horng et al. [22] used the RSM to evaluate the machinability of Hadfield steel in hard turning. The combined effects of four machining parameters, (cutting speed, feed rate, depth of cut and tool corner radius), on the basis of two performance characteristics (flank wear and surface roughness), were investigated; the centered central composite design and the analysis of variance were employed. Results showed that the flank wear was influenced principally by the cutting speed and the interaction effect of feed rate on the nose radius of the tool; the cutting speed and the tool corner radius had a statistical significance on the surface roughness. Davim [23] applied the Taguchi method to investigate the effect of cutting parameters (cutting velocity and feed rate) and cutting time on drilling metal-matrix composites. The analysis of the results showed that the cutting time was the factor which had the greatest influence on the tool wear (50%), followed by the feed rate (24%).

The main problem facing companies in the metal-cutting industry is the need to increase manufacturing quality and at the same time to decrease production costs. There are many variables which affect the quality and production costs of the product, including cutting parameters, tool materials, tool geometry, coating technology, lubricants, etc. Consequently, companies are forced to operate by using the trial and error method. The optimization of controllable variables can make a considerable contribution towards solving the problem. At this point, the variables leading to a final solution are being optimized by using the Taguchi method, thus considerably reducing the number of tests needed. Therefore, by employing the trial and error method, production costs will decrease significantly and time loss will be minimal. As a result, nowadays, this and similar methods have become the focus of interest for both academics and companies, with the goal of increasing production quality and operating with greater efficiency.

In this study, the effects of machining parameters on the surface roughness and flank wear in the milling of Hadfield steel with PVD TiAlN- and CVD TiCN/Al_2O_3-coated carbide inserts were investigated. Taguchi's L18 array was used for conducting the experiments. For the determination of optimal machining conditions (cutting tool, cutting speed and feed rate) for minimum surface roughness and flank wear, Taguchi's signal-to-noise ratio was used. In addition, linear and quadratic regression analyses were applied to predict the measured value. Finally, the reliability of developed models was tested by the confirmation experiments.

2. Experimental methods

2.1. Milling experiments

The milling experiments were carried out in dry cutting conditions using a First MCV 350 model three-axis CNC milling machine equipped with a maximum spindle speed of 8000 rpm and a 7.5-kW drive motor. The experimental