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Optimization of surface roughness, cutting force and tool wear of nitrogen alloyed duplex stainless steel in a dry turning process using Taguchi method

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ABSTRACT

In this work, the dry turning parameters of two different grades of nitrogen alloyed duplex stainless steel are optimized by using Taguchi method. The turning operations were carried out with TiC and TiCN coated carbide cutting tool inserts. The experiments were conducted at three different cutting speeds (80, 100 and 120 m/min) with three different feed rates (0.04, 0.08 and 0.12 mm/rev) and a constant depth of cut (0.5 mm). The cutting parameters are optimized using signal to noise ratio and the analysis of variance. The effects of cutting speed and feed rate on surface roughness, cutting force and tool wear were analyzed. The results revealed that the feed rate is the more significant parameter influencing the surface roughness and cutting force. The cutting speed was identified as the more significant parameter influencing the tool wear. Tool wear was analyzed using scanning electron microscope image. The confirmation tests are carried out at optimum cutting conditions. The results at optimum cutting condition are predicted using estimated signal to noise ratio equation. The predicted results are found to be closer to experimental results within 8% deviations.

1. Introduction

In the past few decades, the applications of stainless steel materials have been increased enormously in various engineering fields. The combination of good corrosion resistance, wide range of strength levels, good formability and aesthetically pleasing appearance have made stainless steels as a good choice for wide range of applications. But, their machinability is more difficult compared to other alloy steels due to low thermal conductivity, high built-up edge (BUE) formation tendency and high deformation hardening. Duplex stainless steel (DSS) combines the benefits of both ferritic stainless steel (FSS) and austenitic stainless steel (ASS) by proper balancing of ferrite and austenite. The duplex structure improves stress-corrosion cracking resistance, compared to ASSs, and improves the toughness and ductility compared to FSSs [1]. Modern DSS grades tend to be difficult to machine, by virtue of their higher austenite and nitrogen contents. The use of DSSs has been increased due to their high strength, higher pitting corrosion resistance equivalent and stress corrosion resistance [2]. DSSs are extensively being used in many industrial sectors like desalination, chemical tankers, pressure vessels, storage tanks, machinery in the pulp and paper industry, and also in civil engineering applications. They have higher contents of chromium and lower contents of nickel and molybdenum and they are excellent engineering materials [3].

Agrawal et al. [4] have been studied the machining characteristics of cast ASSs with reference to cutting force

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requirement, tool rake-face wear and chip characteristics. It has been reported that the composition of stainless steel work piece material influences the machinability. The wear mechanisms when turning X5CrMnN18 ASS materials were catastrophic failure at tool nose due to high cutting forces and sharp edge chipping. The addition of nitrogen to ASS increases the strength and decreases the machinability [5]. In powder metallurgy produced DSSs, the machining difficulties are increased due to the presence of more hard oxide particles, high strength and work hardening rate [6]. The surface roughness values were found to decrease with increasing cutting speed when turning AISI 304 ASS. This can be attributed to the presence of BUE at lower cutting speeds. The poor performance of the tool was due to higher influence of the heat on the cutting tool and less efficient heat dissipation at the lower cutting speeds [7]. Similarly, Ciftci [8] investigated the machining characteristics of ASS using chemical vapor deposition coated carbide cutting tools. His results reported that cutting speed is highly influencing the surface roughness values. In another work, Senthikumar et al. [9] evaluated the tool life of alumina based ceramic cutting tool for machining hardened martensitic stainless steel (MSS). It has been reported that the flank wear affects the tool life at lower cutting speed, whereas, crater wear or notch wear affects the tool life at higher cutting speed. Noordin et al. [10] recommended higher insert radius, low feed rate and low depth of cut to obtain better surface finish under dry turning operation. The flank wear rate of Cubic Boron Nitride (CBN) tool was more compared to Polycrystalline Cubic Boron Nitride (PCBN) tool while machining MSS due to more abrasion and diffusion [11]. Krolczyk et al. [12] developed a mathematical model using response surface method (RSM) to predict the surface roughness of DSS in dry turning. The cutting parameters considered were cutting speed, feed rate and depth of cut. They found that the feed rate is the main influencing factor on the surface roughness. Bouzid Sai et al. [13] investigated the residual stresses, microstructure, surface roughness and micro hardness of carbon steels and DSS materials during milling operations. They found that a high value cutting speed with less feed rate has improved the quality of the machining surface. Depth of cut has less influence on the surface characteristics.

Muthukrishnan and Davim [14] optimized the machining parameters of Al/SiC metal matrix composites using ANOVA and ANN analysis and reported that feed rate has high physical influence on the surface roughness. Similarly, Palanikumar [15] used Taguchi method to optimize the drilling parameters of glass fiber-reinforced plastics composites. It has been reported that feed rate was the more influential parameter than spindle speed. In another work, Mandal et al. [16] applied Taguchi method and regression analysis to assess the machinability of AISI 4340 steel with newly developed Zirconia Toughened Alumina ceramic inserts. Their results reported that the main contributing factors for the tool flank wear are depth of cut and the cutting speed. The feed rate has less influence on the flank wear. Similarly, Asiltürk and Akkus [17] conducted dry turning tests on hardened AISI 4140 steel (51 HRC) with coated carbide cutting tools. They used Taguchi method to optimize the cutting parameters. Their results reported that the feed rate has the more significant effect on surface roughness (Ra- roughness average and Rz-average maximum height of the profile). The cited literatures confirmed that limited investigations have been carried out on the machining characteristics of nitrogen alloyed DSS. Hence, an attempt has been made in this work to optimize the cutting parameters to minimize the surface roughness, cutting force and tool wear during dry turning operations of nitrogen alloyed DSS.

2. Taguchi method

Taguchi method is widely used for optimizing industrial/production processes. The Taguchi design optimization method can be divided into three stages: (a) system design, (b) parameter design and (c) tolerance design. Among the three stages, the parameter design stage is considered to be the important stage [18–20]. The steps followed in the Taguchi parameter design are: selecting the proper orthogonal array (OA); running experiments based on the OA; analyzing data; identifying the optimum condition; and conducting confirmation runs [21]. Many researchers have been used Taguchi method to optimize the various machining operations like turning, end milling, drilling, etc. in various alloys [22–28].

3. Experimental details and data analysis

The experiments are designed using Taguchi's design of experiment method. This research work was carried out at Centre for Research in Design and Manufacturing engineering (CRDM), Karunya University, Coimbatore, India. The experimental data are analyzed by using the signal to noise ratio (S/N ratio) and the analysis of variance (ANOVA). The S/N ratio analysis is used to find out the optimum machining conditions. The ANOVA analysis is used to find the percentage contribution of the cutting speed and feed rate on surface roughness, cutting force and tool wear.

3.1. Work piece material

The work piece materials selected for investigation are the cast DSS ASTM A 995 grade 5A and grade 4A with the compositions as shown in Table 1. The mechanical properties of the material investigated are given in Table 2. The diameter and length of the work piece used in the experimentation are 80 mm and 300 mm, respectively. One end of the work piece is held in a chuck and other end is supported with a tailstock. Generally the length-to-diameter ratio used is 3:1–6:1, while machining with the tail stock to prevent deflection. The length-to-diameter ratio of the specimen used in this work is 3.75:1, which falls within the acceptable range.

3.2. Experimental procedure

The turning tests are conducted on a medium duty Kirloskar Turn master-35 Lathe with a variable speed between 100 and 1500 rpm and a power rating of 2.2 kW.