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OPTIMIZATION OF SURFACE ROUGHNESS OF DUPLEX STAINLESS STEEL IN DRY TURNING OPERATION USING TAGUCHI TECHNIQUE

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Abstract. This paper presents the results of experimental work carried out in dry turning operation of nitrogen alloyed duplex stainless steel ASTM A 995 Grade 5A. In this investigation, the cutting parameters considered were cutting speed, feed rate and depth of cut. The effects of these cutting parameters on the surface roughness were analyzed using Taguchi technique. The results revealed that the feed rate is the most important parameter affecting the surface roughness, followed by cutting speed and depth of cut. The minimum surface roughness was obtained when the process parameters were set at their optimum values.

Keywords: duplex stainless steel, dry turning, surface roughness, Taguchi technique

1. Introduction

Stainless steels are iron-base alloys that contain a minimum of approximately 11% Cr, the amount needed to prevent the formation of rust in unpolluted atmospheres. Duplex stainless steels (DSSs) are chromium-nickel-molybdenum alloys that are balanced to contain a mixture of austenite and ferrite and are magnetic. But their machinability is more difficult than other alloy steels due to the reasons like low heat conductivity, high built up edge formation tendency, high deformation hardening and so on. DSS combines the benefits of both Ferritic stainless steel (FSS) and austenitic stainless steels (ASS) by proper balancing of ferrite and austenite. [1]. Machinability aspect is importance for manufacturing engineers to know about the machinability of a work material so that the processing can be planned in an efficient manner. 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 because of their high strength, higher pitting corrosion resistance equivalent and stress corrosion resistance. DSSs are used in desalination plants and other industrial applications [2]. DSSs are extensively being used within a number of industry sectors outside desalination, e.g. chemical tankers, pressure vessels, storage tanks and oil and gas, petrochemical, pulp and paper, pollution control industries and civil engineering applications. The DSSs are less costly due to lower contents of mainly nickel and molybdenum, and they are excellent engineering materials [3].

Ciftci [4] investigated the machining characteristics of AISI 304 and AISI 316 ASSs using coated carbide tools. They reported that the increase in cutting speed decreased the surface roughness values until a minimum value and beyond which they increase. Korkut et al. [5] carried out turning tests to determine optimum machining parameters for machining of ASS. They reported that the Surface roughness values were found to decrease with increasing cutting speeds. Xavior et al. [6] investigated the influence of cutting fluids on tool wear and

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surface roughness during turning of AISI 304 with carbide tool. The use of coconut oil as cutting fluid improved the surface roughness during turning process. Kaladhara et al. [7] used Taguchi method to determine the optimum process parameters for turning of AISI 304 ASS on CNC lathe using coated cemented carbide cutting insert. Their results revealed that the cutting speed was the dominant parameter which affects the surface roughness. Koyee et al. [8] conducted turning tests on ASS and DSSs applying Taguchi coupled Fuzzy Attribute Decision Making (FMADM) methods for optimize the surface roughness. They found that the feed rate was the predominant parameter which affects the surface roughness. Selvaraj et al. [9] conducted turning experiments to optimize the cutting force, surface finish, and tool wear of cast DSS. They reported that higher cutting speed and lower feed rate gave lower surface roughness and cutting force.

From the literature stated above, it is clear that many research works have been carried out in the machining of ASS. But few reports could be found on the machining of DSS and the machining of nitrogen alloyed DSS are yet to be investigated. Surface roughness is the vital machinability index to evaluate the machining characteristics of the materials. Therefore in this work the machining studies of nitrogen alloyed DSS are carried out to understand the influence of the cutting speed, feed rate and depth of cut on the surface roughness using Taguchi technique.

2. Taguchi method

Taguchi method provides a simple, efficient and systematic approach to determine optimal machining parameters. Taguchi method uses an orthogonal array (OA) to study the entire process with only a small number of experiments. The Taguchi design method can be divided into three stages: system design, parameter design, and tolerance design. The second stage-the parameter design-is considered to be the most important stage [10, 11]. Several researchers have been applied Taguchi technique to optimize the cutting parameters in various machining operations like turning, end milling, drilling, flow forming etc in various alloys [11-16].

3. Experimental procedure

Work Piece Material. The work piece material selected for investigation was the cast nitrogen alloyed DSS ASTM A 995 grade 5A with the chemical composition as shown in Table 1. The mechanical properties of the material investigated are given in Table 2.

Table 1. Chemical composition of ASTM A 995 grade 5A DSS (Wt %)

C	Si	Mn	S	P	Cr	Ni	Mo	N	Fe
0.028	0.67	0.87	0.005	0.028	25.10	6.63	4.16	0.17	Bal

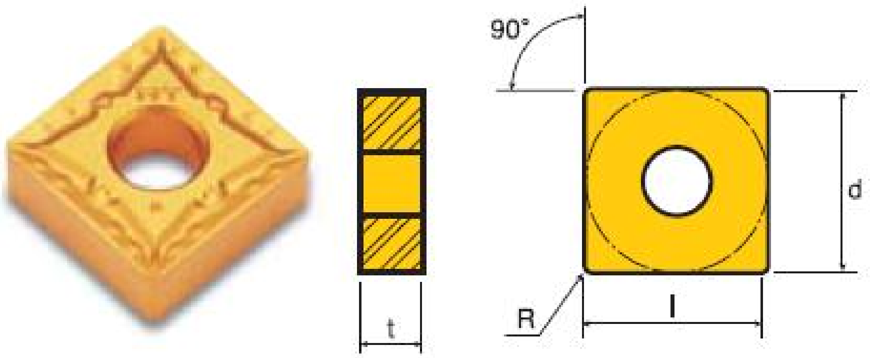
Table 2. Mechanical properties of ASTM A 995 grade 5A DSS

Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Hardness (BHN)
741	546	32.2	223

Machining process. The turning tests are conducted on a Kirloskar Turn master-35 Lathe with a power rating of 3HP. The power rating of the variable feed motor is 1HP. The variable speed and feed controller are used to adjust the speed and feed rates. The diameter and length of the cylindrical work piece used in the turning experiments are 80 mm and 300 mm, respectively.

The cutting tools used are carbide inserts (Taegu Tec make) coated with TiC and TiCN with a specification of SNMG 120408 MT TT5100. The inserts are clamped on a pin and hole type tool holder (Taegu Tec make) with a specification of PSBNR 2525M12. The tool holder is shown in Fig. 1. The basic forms and geometries of the tool insert are shown in Fig. 2. The dimensions of the inserts are given in mm. Surface roughness was measured using a portable TIME surface roughness tester (TR100). A cut-off length of 2.5 mm was used for taking the surface roughness measurements. The experiments were conducted without the application of cutting fluid (dry turning).

Fig. 1. Tool holder



l = 12.7, d = 12.7, t = 4.76 and R = 0.8

Fig. 2. Turning tool insert

Plan of experiments. There are several parameters that could be considered for machining of a particular material in turning operation. However, the review of literature shows that cutting speed, feed rate and depth of cut are the most significant cutting parameters to control the turning process. Hence in the present study cutting speed, feed rate and depth of cut are selected as the machining parameters while the other parameters such as nose radius and tool angles are kept as constant [11, 17, 18]. For 3 levels and 3 factor experiments, the turning tests are planned using the Taguchi's L_9 OA. For turning DSS material using carbide cutting tool, the cutting speed range is 80-120 m/min as per the standard published by International Molybdenum Association (IMOA 1999). Based on the tool manufacturer recommendation, preliminary experiments are conducted and feasible range of feed rate (0.04

to 0.12 mm/rev) and depth of cut (0.4 to 1.2 mm) are selected for the present study. The experiments are 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 three different depth of cuts (0.4, 0.8 and 1.2 mm). The cutting parameters and their levels in dry turning operation are indicated in Table 3. The experimental layout using L_9 OA for dry turning is shown in Table 4.

Table 3. Cutting parameters and their levels in dry turning operation

Symbol	Cutting parameters	Level 1	Level 2	Level 3
V	Cutting speed (m/min)	80	100	120
F	Feed rate (mm/rev)	0.04	0.08	0.12
D	Depth of cut (mm)	0.4	0.8	1.2

Table 4. Experimental layout using L_9 OA for dry turning operation

Experimental number	Cutting parameter level		
	V	F	D
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

4. Analysis of Experimental Results

The experiments are conducted according to a 3-level and 3-factor L_9 OA. The experimental results for surface roughness during dry turning of 5A grade DSS is given in Table 5. The experimental results are analyzed to find out the main effects and their difference between level 1 and 2, level 2 and 3 and level 3 and 1 of the input parameters on the surface roughness. In the present study, Taguchi analysis is conducted using average-of-results methodology. Design of experiment software Qualitek-4 is used for this analysis.

In order to calculate the main effects and their differences, first the overall mean of the surface roughness is calculated by using the equation (1) discussed by Phadke [19].

$$\text{Mean Ra} = \frac{1}{9}\sum_{i=1}^{9} \text{Ra} = 1.249 \ \mu\text{m}. \quad (1)$$

The main effect of cutting speed, V at level 1 (i.e., = 80 m/min), on surface roughness is calculated by using the Equation (2) discussed by Phadke [19].

$$\text{Mean Ra for V at level 1} = \frac{\text{Ra1+Ra2+Ra3}}{3} = 1.293 \ \mu\text{m}. \quad (2)$$

Table 5. Experimental results for surface roughness during dry turning operation

Exp. No.	Parameter level			R_a (µm)
	V	F	D	
1	1	1	1	1.18
2	1	2	2	1.29
3	1	3	3	1.41
4	2	1	2	1.12
5	2	2	3	1.21
6	2	3	1	1.24
7	3	1	3	1.22
8	3	2	1	1.23
9	3	3	2	1.34

The main effects and their difference between levels associated with the surface roughness of 5A grade DSS during dry turning operation is given in Table 6.

Table 6. Main effects and their differences on the surface roughness in dry turning operation

Factors	Level 1 (L_1)	Level 2 (L_2)	Level 3 (L_3)	Difference between levels		
				L_2-L_1	L_3-L_1	L_3-L_2
V (mm/min)	1.293	1.189	1.263	-0.104	-0.030	0.073
F(mm/rev)	1.173	1.243	1.330	0.070	0.157	0.086
D (mm)	1.216	1.250	1.279	0.034	0.062	0.028

During dry turning of 5A grade DSS, the change of cutting speed from 80 to100 m/min decreases the main effects of surface roughness from a mean value of 1.293 to 1.189 µm. The change of cutting speed from 100 to 120 m/min increases the main effects of surface roughness from a mean value of 1.189 to 1.263 µm. Generally surface finish increases with increase of cutting speed. At lower cutting speed (80 m/min), surface finish is poor due to built-up edge formation tendency. When the cutting speed is increased from 80 to 100 m/min, the built-up edge size starts decreasing and disappears owing to increased tool temperature. However, as the cutting speed increases from 100 to 120 m/min, the tool temperature increased and softened the tool materials. Hence abrasive, adhesive and diffusive wear are occurred in the tool. Hence, at higher cutting speed, surface finish is reduced due to the tool wear [9, 20]. Therefore, medium cutting speed (100 m/min) is the optimal cutting speed which gives better surface finish in the present work. The change of feed rate from 0.04 to 0.08 mm/rev increases the main effects of surface roughness from a mean value of 1.173 to 1.243 µm. The change of feed rate from 0.08 to 0.12 mm/rev increases the main effects of surface roughness from a mean value of 1.243 to 1.330 µm. The change of depth of cut from 0.4 to 0.8 mm increases the main effects of surface roughness from a mean value of 1.216 to 1.250 µm. The change of depth of cut from 0.8 to 1.2 mm increases the main effects of surface roughness from a mean value of 1.250 to 1.279 µm. The surface roughness value increases with increase in feed rate and depth of cut. As the feed rate and depth of cut is increased, the area of contact between tool and work and the volume of material removed by the tool increases. Hence cutting force increases which leads to increase in surface roughness.

The main effects and their difference between levels of the cutting parameters on the surface roughness of 5A grade DSS during dry turning operation is shown in Fig. 3. The relative slopes of linear graphs indicate significance of the cutting parameters [15]. Here the slope of the line showing the influence of the feed rate is higher compared to the slope of the cutting speed and depth of cut. Hence, the feed rate is the most significant cutting parameter for surface roughness followed by the cutting speed and the depth of cut. The lowest main effect for surface roughness is obtained when the cutting speed is at level 2, feed rate at level 1 and depth of cut at level 1. Therefore the optimal cutting parameters for surface roughness are the cutting speed at level 2 (100 m/min), the feed rate at level 1 (0.04 mm/rev) and depth of cut at level 1 (0.4 mm).

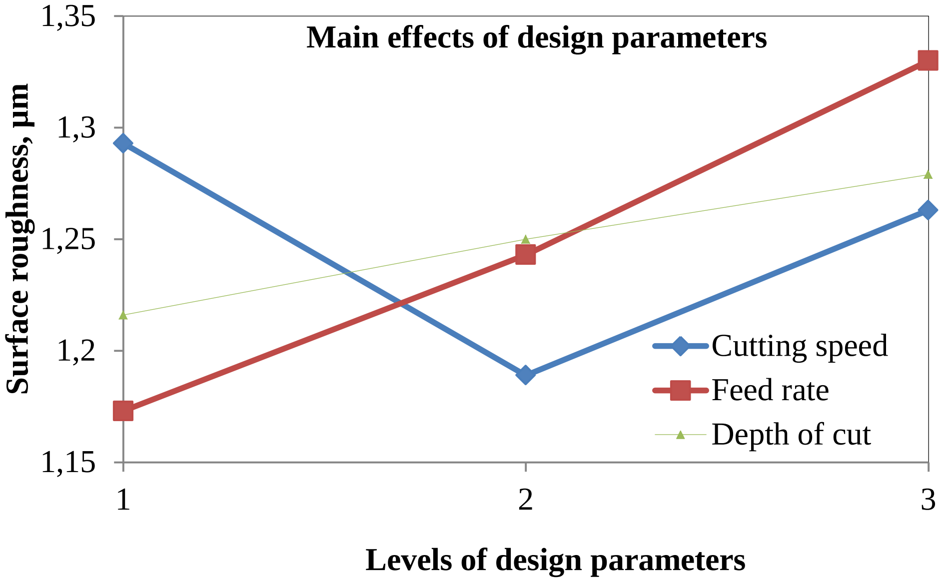


Fig. 3. Main effects of the design parameters on surface roughness during dry turning operation

At lower cutting speed, the built-up edge formation tendency is more. Therefore, the cutting speed has more influence on the surface roughness at lower cutting speed. At higher cutting speed, the built-up edge formation tendency is decreased and disappeared. Therefore, the cutting speed has less influence on the surface roughness at higher cutting speed.

The average surface roughness, Ra is given by the following equation discussed by Juneja et al. [21].

$$\text{Average surface roughness, Ra} = \frac{0.2566\, f^2}{r_n}. \quad (3)$$

Here, f is the feed rate in mm/rev and r_n is the nose radius in mm.

In the present work nose radius (r_n) is kept as constant. Hence, from the equation (3) surface roughness depends only on feed rate. The equation (3) does not consider the effects of cutting speed and depth of cut. Hence, this equation does not give correct results in practical applications. Basically, surface roughness is correlated strongly with machining parameters such as cutting speed, feed rate and depth of cut in turning operation. Hence, for more accurate results surface roughness model is developed by researchers using regression method and Response surface methodology (RSM).

The results of the ANOVA for the surface roughness of 5A grade DSS in dry turning operation is given in Table 7. It can be observed that the feed rate is the most significant cutting parameter affecting the surface roughness in dry turning operation of DSS. The contribution order of the cutting parameters for affecting the surface roughness is feed rate, cutting speed and then depth of cut. ANOVA results show that the feed rate, cutting speed and depth of cut affect the surface roughness by about 61%, 28% and 10%, respectively.

Table.7 ANOVA results for surface roughness during dry turning operation

Cutting Parameter	DOF	SS	MS	F-Ratio	Contribution (%)
V	2	0.016	0.008	107.761	27.95
F	2	0.036	0.018	234.897	61.24
D	2	0.006	0.003	32.278	9.76
Error	2	0.002	0.001		1.05
Total	8	0.060			100

Table.8 Optimum condition for minimum surface roughness during dry turning operation

Factor	Level description	Level	Contribution
V	100	2	-0.059
F	0.04	1	-0.076
D	0.4	1	-0.033

Table 8 gives the optimum cutting conditions for achieving minimum surface roughness for 5A grade DSS during dry turning operation. It reveals that for optimal surface roughness, the cutting speed should be at level 2, the feed rate should be at level 1 and the depth of cut should be at level 1. The total contribution from the three input parameters is -0.168. It provides the contribution that a parameter has made to improve the expected response. The current grand average of performance is 1.249 µm. It is the overall mean of all trials. Expected surface roughness value at optimum condition is 1.08 µm. Experimental surface roughness value at optimum condition is 1.03 µm.

5. Conclusions

The Taguchi technique was applied to find the optimal process parameters of nitrogen alloyed duplex stainless steel during dry turning process. The variables affecting the surface roughness according to their relative significance were the feed rate, the cutting speed and the depth of cut.

The ANOVA results revealed that the feed rate, the cutting speed and the depth of cut were affecting the surface roughness by about 61%, 28% and 10%, respectively. The optimum surface roughness was obtained when the cutting speed was at 100 m/min, the feed rate at 0.04 mm/rev and the depth of cut at 0.4 mm. It was found that the optimum levels of cutting parameters ensured significant improvement in the surface finish.

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