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EXPERIMENTAL INVESTIGATIONS OF NITROGEN ALLOYED DUPLEX STAINLESS STEEL IN DRY MILLING PROCESS

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Abstract

Duplex stainless steels are generally more difficult to cut because of their high toughness, low heat conductivity, more strain hardening rate and more built-up edge formation. Milling is an important machining process for manufacturing flat, curved and profiled surfaces. In this work, an attempt has been taken to investigate the machining performance of two different types of cast duplex stainless steels in dry milling operation using coated tungsten carbide tools. A 15 run experiment was designed to investigate the effect of spindle speed and feed rate on the surface roughness and cutting force. The end milling experiments were conducted with five different spindle speeds and three different feed rates with a constant axial depth of cut. The result revealed that the increasing spindle speed decreased the surface roughness and the cutting force values up to 1000 rpm and then increased. The increase of feed rate increased the surface roughness and cutting force values. The presence of higher austenite in 5A grade duplex stainless steel was responsible for higher surface roughness and cutting force values compared with 4A grade duplex stainless steel.

Keywords: Duplex stainless steel, Dry milling, Surface roughness, Cutting force.

1. Introduction

Duplex stainless steels (DSSs) contain approximately equal amount of ferrite and austenite phases in their microstructure. The duplex structure improves the stress-

Nomenclatures

F	Feed rate, mm/min
F_c	Cutting force, N
N	Spindle speed, rpm
R_a	Surface roughness, μm

Abbreviations

ASS	Austenite stainless steel
BBD	Box-Behnken design
BHN	Brinell hardness number
BUE	Built up edge
DSS	Duplex stainless steel
FMADM	Fuzzy Multi Attribute Decision Making
FSS	Ferritic stainless steel
RSM	Response surface methodology
TiCN	Titanium Carbo Nitride

corrosion cracking resistance, toughness and ductility of this alloy. These steels have annealed yield strengths ranging from 550 to 690 MPa, which is quite higher than the strength level of ferritic stainless steels (FSSs) and austenite stainless steels (ASSs). The addition of nitrogen to DSS alloys increases the amount of austenite to nearly 50%. In addition, nitrogen improves as- welded corrosion properties, chloride corrosion resistance, and toughness. The improvement in toughness is probably due to the higher amount of austenite present, which makes it possible in producing heavier product forms such as plates and bars [1]. DSS alloys have chemistry similar to ASS alloys. They are generally more difficult to cut because of their high toughness. Machining DSS alloys can be particularly challenging to machine tool industries because no standard enhanced machining grades are available [2]. Currently the manufacturing industries are facing difficulties in machining DSS components due to their low heat conductivity, more strain hardening rate and more built-up edge (BUE) formation.

DSSs are commonly used in aqueous and chloride-containing environments. They are used in chemical, petrochemical and marine industries. They are also used in tubing for heat exchangers in refineries, process industries, chemical tankers, chemical reactor vessels, pressure vessels, storage tanks, flue gas filters, acetic and phosphoric acid handling systems, domestic water heaters, pipe for sea water handling, fire fighting systems, oil and gas separators, salt evaporation equipments, desalination plants, energy recovery systems, geothermal well heat exchangers, human body implants, pulp and paper industries and civil engineering applications [1, 3].

Bordinassi et al. [4] studied the machinability of ASTM A890 grade 6A DSS during turning operation using carbide tools. The feed rate was most significant and the depth of cut was less significant factor for the surface finish. The surface finish was improved by using the cutting fluid [5]. The decrease in the BUE formation tendency at higher cutting speed resulted better surface finish [6]. Selvaraj and Chandramoha [7] studied the effect of cutting velocity, feed and bulk texture on the surface roughness of DSS alloys during turning process. They reported that cutting velocity, feed and bulk texture of the material were significant parameters to achieve the minimum surface roughness during turning operation. Krolczyk et al. [8] optimized surface roughness by applying response surface methodology (RSM) in dry turning operation of DSS. The machining parameters considered were cutting velocity, feed and depth of cut. They found that the feed was the most important factor which influences the surface finish.

Koyee et al. [9] conducted turning tests on ASS and DSSs using Taguchi coupled Fuzzy Multi Attribute Decision Making (FMADM) methods for optimize the surface roughness during turning operation. They found that the feed rate was the predominant parameter which affects the surface roughness. Selvaraj et al. [10] conducted turning experiments to optimize the cutting force, surface finish, and tool wear of cast nitrogen alloyed DSSs. They reported that higher cutting velocity and lower feed gave lower surface roughness and cutting force. Koyee et al. [11] developed mathematical models for radial cutting force, effective cutting power and tool wear of EN 1.4462 and EN 1.4410 DSSs in turning operations. Thiyagu et al. [12] used Box-Behnken design (BBD) RSM to optimize surface roughness and cutting force of DSS in turning operation. They reported that the predominant parameter to achieve better surface finish was feed rate. They reported that feed rate and nose radius were significant parameters to achieve the minimum cutting force.

Sai et al. [6] carried out face milling studies of DSS and carbon steels. They reported that the combination of higher spindle speed and lower feed were chosen for better surface finish. Depth of cut had less effect on the surface finish. Machining with lower cutting speed gave poor surface quality because of BUE formation. Selvaraj et al. [13] optimized cutting conditions to minimize surface roughness, cutting force and tool wear during end milling operation of 5A grade DSS using Taguchi Technique. Philip et al. [14] used BBD RSM to optimize the surface roughness of DSS in milling operation. They reported that the optimal surface finish was obtained while using higher spindle speed, lower feed and lower axial depth of cut.

The various literatures cited above reveals that many experimental investigations have been reported on machining characteristics of DSS in turning operation. But very few research works have been reported in milling operation of DSS. The comparison of machining performance of 4A and 5A grade DSS was not reported in milling operation. Hence, in the present work, the influence of spindle speed and feed rate on surface roughness and cutting force has been investigated in end milling operation of 4A and 5A grade cast nitrogen alloyed DSS.

2. Materials and methods

The materials selected for investigation are the DSS ASTM A 995 grade 4A and 5A. The materials were supplied by Auto Shell Casts Private Limited, Coimbatore, India. The chemical compositions of the material investigated are provided in Table 1 and the mechanical properties are given in Table 2.

Table 1.Chemical composition of grade 4A and 5A DSS (wt %) [15].

Element	4A DSS	5A DSS
C	0.028	0.028
Si	0.65	0.67
Mn	0.71	0.87
S	0.006	0.005
P	0.027	0.028
Cr	22.16	25.10
Ni	5.66	6.63
Mo	3.33	4.16
Cu	0.14	0.00
N	0.17	0.24
Fe	Balance	Balance

Table 2.Mechanical properties of grade 5A and 4A DSS (annealed) [15].

Property	4A DSS	5A DSS
Tensile Strength (MPa)	732	741
Yield Strength (MPa)	595	546
Elongation (%)	30.2	32.2
Hardness (BHN)	212	223

The dimensions of the work piece materials used for the present investigation are 120 mm length, 100 mm width and 30 mm thickness. The milling tests were carried out using a HMT FN1U semi automatic milling machine. The power rating of the milling machine spindle motor and feed motor are 2.2 kW and 0.75 kW, respectively. The specification of the 20 mm diameter end mill cutter used in the experiment was TE90AX 220-09-L. The specification of TiCN coated tungsten carbide inserts used in the experiment was AXMT 0903 08 PER-EML TT8020. Kistler dynamometer (model 9257B) was used for measuring the cutting force. Spindle speed, feed rate and axial depth of cut are the main cutting parameters for milling operation.

The effect of cutting speed and feed rate are more significant than depth of cut [6, 16]. Thakur et al. [17] maintained depth of cut as constant in turning operation. Shao et al. [18] maintained axial depth of cut as constant in milling operation. Hence, in this study spindle speed and feed rate are selected as the main machining parameters and axial depth of cut is taken constant as 0.5 mm. The spindle speeds used in this experimentation range from 350 to 1400 rpm. The feed rates used range from 63 to 160 mm/min. Cutting fluid was not applied while conducting the experiments (dry milling). TIME TR100 surface roughness instrument was used for measuring the surface roughness (R_a). The experimental setup is illustrated schematically in Fig.1.

3. Results and discussion

The milling tests were carried out with five levels of spindle speeds with three levels of feed rates and the cutting force and surface roughness were measured. The results for the cutting force and surface roughness of 4A and 5A grade DSS are given in Table.3.

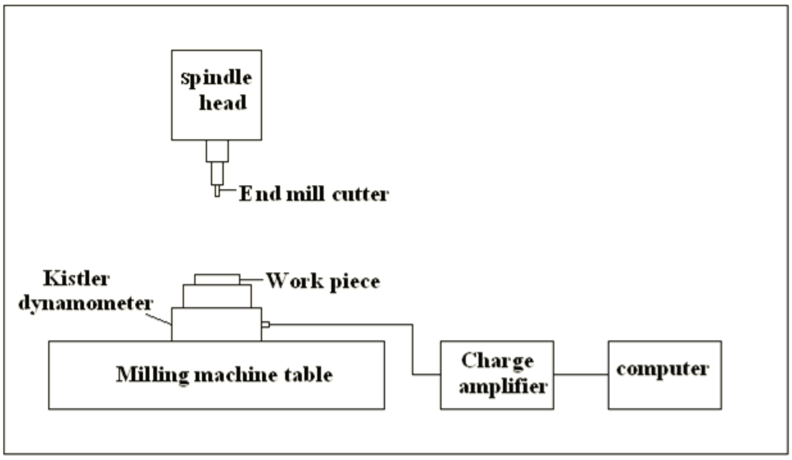


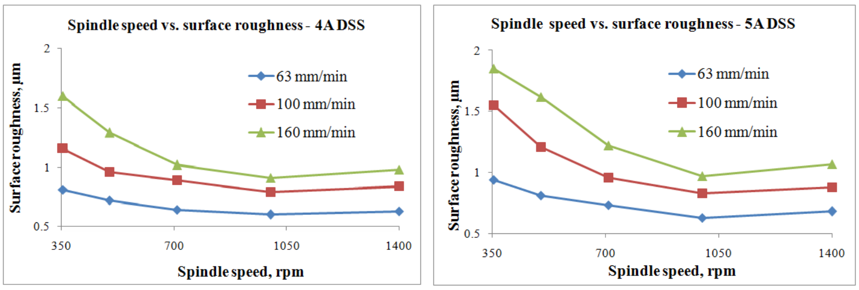
Fig. 1. Schematic diagram of experimental setup.

Table 3. Experimental results for surface roughness and cutting force of 4A and 5A grade DSS.

Exp. No.	**Spindle speed,** *N(rpm)*	**Feed rate,** *f (mm/min)*	**Surface roughness,** *Ra* (μm)		**Cutting force,** *Fc* (*N*)	
			4A DSS	**5A DSS**	**4A DSS**	**5A DSS**
1	355	63	0.81	0.94	207	221
2	500	63	0.72	0.81	146	191
3	710	63	0.64	0.73	134	172
4	1000	63	0.60	0.63	115	160
5	1400	63	0.63	0.68	123	169
6	355	100	1.16	1.55	225	239
7	500	100	0.96	1.21	170	226
8	710	100	0.89	0.96	159	201
9	1000	100	0.79	0.83	152	185
10	1400	100	0.84	0.88	156	196
11	355	160	1.60	1.85	248	297
12	500	160	1.29	1.62	205	252
13	710	160	1.02	1.22	186	229
14	1000	160	0.91	0.97	164	198
15	1400	160	0.98	1.07	175	207

3.1. Effect of machining parameters on surface roughness and cutting force

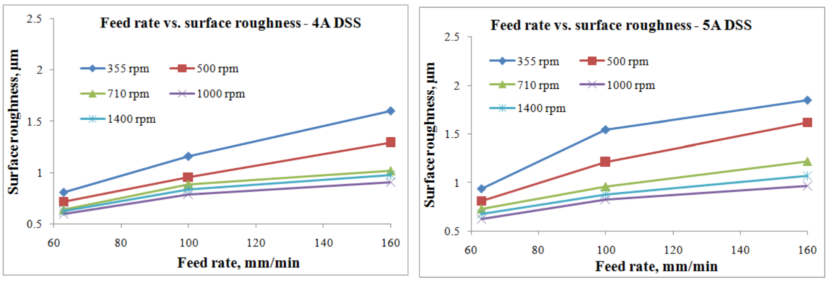
The effect of spindle speed on surface roughness of 4A and 5A grade DSS for three levels of feed rates during dry milling operation is illustrated in Figs. 2(a) and (b), respectively. When spindle speed increases the surface roughness value decreases up to 1000 rpm. However further increase in spindle speed increases the surface roughness values. The increasing spindle speed from 350 to 1000 rpm reduces the surface roughness value due to the reduction in BUE formation tendency. However, further increase in spindle speed from 1000 to 1400 rpm increases the surface roughness value. This can be attributed due to higher wear rate of tool inserts at higher spindle speed of 1400 rpm. The cutting edge geometry deteriorates with tool wear. The tool having high wear rate requires higher cutting force to remove material from the work piece. Hence surface roughness value is increased. It can be noticed that the minimum surface roughness is obtained when the spindle speed is at 1000 rpm.



(a) 4A DSS. **(b) 5A DSS.**

Fig. 2. Spindle speed vs. surface roughness.

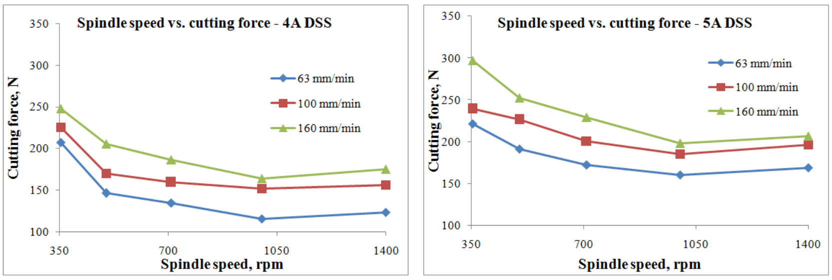
The effect of feed rate on surface roughness of 4A and 5A grade DSS for five levels of spindle speeds during dry milling operation is shown in Figs. 3(a) and (b), respectively. The increasing feed rate increases the surface roughness value. The increase in feed rate increases the heat generation due to increase in material removal rate. This increased heat generation results higher values of surface roughness on the work piece surface [17]. The increase in feed rate also increases the cutting force due to increase in area of contact between tool and work which increases the surface roughness. It can be noticed that the minimum surface roughness is obtained at the feed rate of 63 mm/min for both 4A and 5A grade DSS alloys.



(a) 4A DSS. **(b) 5A DSS.**

Fig. 3. Feed rate vs. surface roughness.

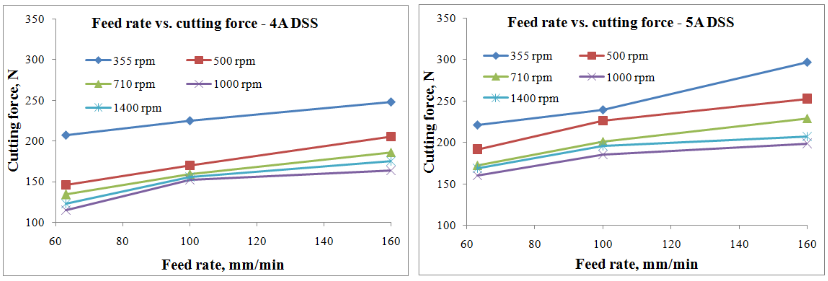
The influence of spindle speed on cutting force during dry milling operation of 4A and 5A grade DSS for three levels of feed rates is depicted in Figs. 4(a) and (b), respectively. The cutting force decreases with increasing spindle speed up to 1000 rpm. However, further increase in spindle speed increases the cutting force values for both the grades. At lower spindle speed, the cutting force values increased due to increase in frictional coefficient between the work piece and tool insert material. This is due to high friction in the tool-chip interface and extreme pressure in the cutting zone. The heat generation rate is more at higher spindle speed. So the material becomes soft at cutting zone. Hence, lower cutting forces are required for machining the material at higher spindle speeds. The chips carry away most of the heat while machining at higher spindle speed. The chip gets thinner and cutting force value decreases with increasing spindle speed. This is due to reduction in tool - work contact area and partly by reduction in shear strength in the cutting zone [19]. However, at 1400 rpm spindle speed this trend changes and cutting force increases. This may be due to more tool wear rate at this spindle speed. It can be noticed that the minimum cutting force is obtained when the spindle speed is at 1000 rpm.



(a) 4A DSS. **(b) 5A DSS.**

Fig. 4. Spindle speed vs. cutting force.

The effect of feed rate on cutting force during dry milling operation of 4A and 5A grade DSS for five different levels of spindle speeds is given in Figs. 5(a) and (b), respectively. It is noticed that the cutting force increases with the increase in feed rate. When the feed rate is increased from 63 to 160 mm/min, the cutting force values increase linearly in all the five levels of spindle speeds. At higher feed rates, the frictional coefficient between the tool insert and work material is higher when compared to lower feed rates because of increase in contact area. The volume of material removed from the work piece also increases at higher feed rate. Hence, higher cutting forces are required to sheer the material. It can be observed that the minimum cutting force is obtained when the feed rate is at 63 mm/min.



(a) 4A DSS. **(b) 5A DSS.**

Fig. 5. Feed rate vs. cutting force.

3.2. Effect of work piece material on surface roughness and cutting force

It is observed from Table 3, that the cutting force and surface roughness values of 4A grade DSS are lower when compared to 5A grade DSS in all the trials. This is basically due to the variation in chemical compositions of the two grades of DSSs [20]. In general, the effect of alloying elements like Cr, Mo, Ni and N in phase formation are remarkable. Ni and N are austenite stabilizers. Due to these reasons, purposely Ni content and N content were increased to 6.63 % and 0.24 %, respectively in the 5A grade melt, aiming for higher austenite. Hence there is a change in volume percentage of ferrite and austenite phase in the microstructure of both the grades. The microstructure of 4A and 5A grade DSS are given in Figs. 6 and 7, respectively [15]. Dark matrix represents ferrite phase and lighter colonies represents austenite phase. Naked eye visualization of microstructures does not reveal significant variation in the volume fraction of ferrite and austenite. Hence, for more clarity an image analysis software package, Image J is used to determine the volume fraction of the ferrite and austenite phase in 4A and 5A grade DSS alloys.

The input for the software is the microstructures of the 4A and 5A grade DSS obtained from the microscopy examination. The software examines the edges to perform morphology measurements. It is determined from the image analysis that the microstructure of 4A grade DSS contains 55 % ferrite and the remaining is austenite whereas the microstructure of 5A grade DSS contains 48 % ferrite and the remaining is austenite. The presence of higher austenite in 5A grade DSS is the basic reason for the blend of higher hardness and strength when compared to 4A grade DSS. In the ferrite matrix, the austenite particles restrict the ferrite grain boundaries movement. This is due to substitutional and interstitial solid solution hardening and increase in strength by grain refinement [21, 22]. In 5A grade, austenite has nucleated more than the 4A grade which has relatively increased the work hardening component. Hence higher machining forces are required for shearing of the 5A grade DSS, which leads to higher surface roughness values in 5A grade DSS as compared to 4A grade DSS.

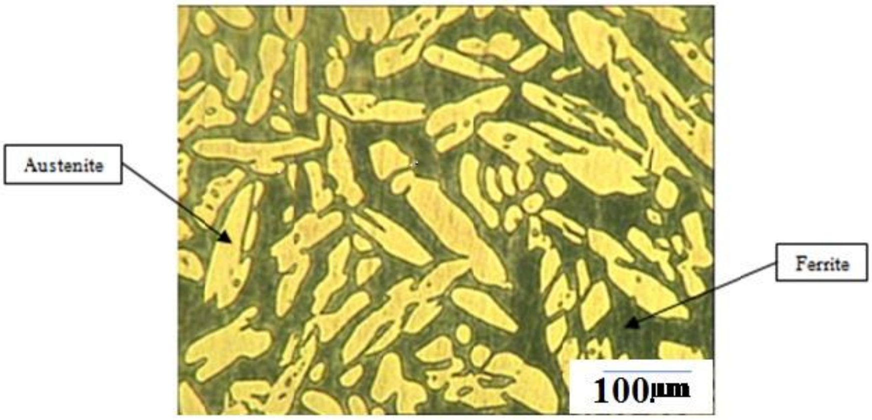


Fig. 6. Microstructure of 4A grade DSS.

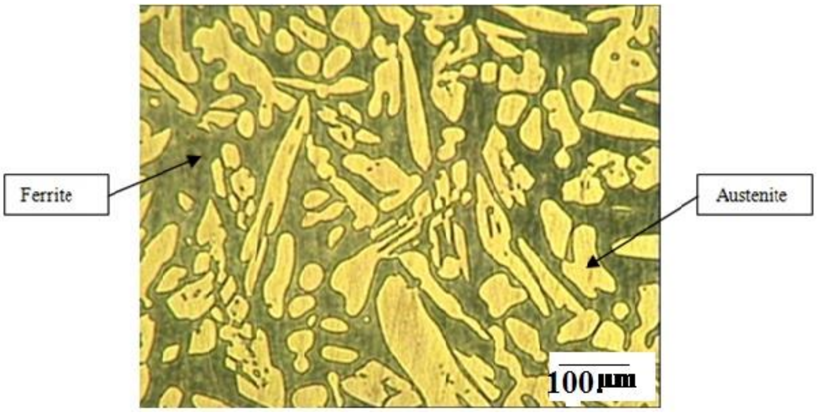


Fig. 7. Microstructure of 5A grade DSS.

4. Conclusions

The dry milling operations were successfully carried out to investigate the influence of spindle speed and feed rate on surface roughness and cutting force of cast nitrogen alloyed DSS. The following conclusions are made from this experimental investigation.

- The cutting force and surface roughness were significantly affected by the feed rate and the spindle speed. The cutting force and surface roughness values were decreased with increasing spindle speed from 350 to 1000 rpm. Further increase in spindle speed resulted higher cutting force and surface roughness. At higher spindle speeds, the values of cutting force and surface roughness were increased due to high tool wear.
- Cutting force and surface roughness were increased with increasing feed rate from 63 to 160 mm/min. At higher feed rates, cutting force and surface roughness were increased due to increase in tool and work contact area.
- A spindle speed of 1000 rpm and a feed rate of 63 mm/min were preferred to minimize the cutting force and surface roughness for both 5A and 4A grade DSS.
- 5A grade DSS yielded higher cutting force and surface roughness values compared with 4A grade DSS due to variation of chemical composition and presence of higher austenite in 5A grade DSS.

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