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CUTTING FORCE STUDIES OF CAST NITROGEN ALLOYED DUPLEX STAINLESS STEEL IN DRY TURNING PROCESS

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Abstract

Cutting force studies in dry turning operation of two grades of cast nitrogen alloyed duplex stainless steels (DSS) are presented in this paper. A 15-run experiment was designed to analyse the machining performance. The turning tests were performed with three different feeds (0.08, 0.10 and 0.12 mm/rev), five different cutting speeds (80, 100, 120, 140 and 160 m/min) and a constant depth of cut (0.5 mm). The turning tests were conducted by using TiCN-Al_2O_3-TiN coated carbide cutting tool inserts. The impact of grade of work piece, feed and cutting speed were investigated. The rise of cutting speed reduces the machining force initially and then increases. Higher tool wear is the reason for the higher values of cutting force at higher cutting velocities. The rise in feed results rise in machining force. Increase in tool work contact area and material removal rate are the reasons for higher values of F_c at higher feed rates. The minimum machining force value was obtained at a feed rate of 0.04 mm/rev and a cutting speed of 120 m/min. Higher percentage content of Ni, Mo and Cr in 5A DSS increases the strength and hardness of this alloy. Hence, higher values of cutting forces are needed for machining 5A DSS alloy than 4A DSS alloy.

Keywords: Carbide tool, Cutting force, Dry turning, Duplex stainless steel.

1. Introduction

The trend of stainless steel (SS) usage has been growing in industries since 1970. SS is considered as one of the most difficult to cut steel alloy. Duplex stainless steel (DSS) has two phase microstructures. They have better stress cracking corrosion resistance and high strength [1]. Generally machinability of work material can be evaluated based on machining force, tool life and quality of surface [2, 3].

Agrawal et al. [2] investigated machining of austenitic stainless steel (ASS) based on cutting force (F_c) and wear of tool. They reported that presence of variation in alloying elements impacts the machining performance of SS alloy. Tool wear mechanisms of ASS in turning operation was investigated by Paro et al. [3]. Chipping and high F_c are the two causes for the catastrophic tool failure. Addition of Nitrogen to ASS increases the machining difficulties. Machining studies of ASSs with inclusion of additives were investigated by Akasawa et al. [4]. The machining forces were reduced by copper addition and resulfurization. Calcium treated steels have improved machinability compared with plain ASSs. Ciftci [5] conducted machining studies of AISI 304 and 316 ASSs by employing carbide tools in computer numerical control (CNC) turning process. He found that the F_c needed for machining SS 316 was higher compared with SS 304. The 2 % of Mo in SS 316 produced larger machining forces.

Lalwani et al. [6] used response surface methodology (RSM) to study the impact of cutting parameters on the F_c and surface roughness (R_a) in hard turning. Depth of cut and feed were the dominant parameters for the machining forces. Selvaraj [7] studied the impact of cutting variables on F_c in DSS milling operation by using Taguchi approach. He concluded that the dominant factor impacting the F_c was feed rate. Selvaraj et al. [8] studied the impact of cutting variables on R_a and F_c of DSS alloys in milling process. Machining force prediction model was developed by Hanief et al. [9] for turning process of brass. Rise of depth, feed, and cutting speed resulted rise of machining force. They found that depth was insignificant, and feed was most significant factor impacting the machining force.

Krolczyk et al. [10] studied the impact of R_a, F_c and tool life in turning operation by using three different carbide tools. The tests were conducted in dry and wet conditions. The results revealed that dry turning with proper selection of tool insert grade, low feed and high cutting speed gave lower F_c and higher tool life than wet turning. The use of cutting fluids leads to negative ecologic, environmental and health issues. Dry turning eliminates these problems. Rajaguru and Arunachalam [11] investigated the performance of four types of coated tools in dry turning process of super duplex stainless steels (SDSS). It is found that [MT-TiCN]-Al_2O_3 coating gave better performance in-terms of tool wear, surface integrity, cutting force and temperature than other coatings followed by TiOCN- Al_2O_3 -TiCN-[MT-TiCN]-TiN, AlTiN and TiN-[MT-TiCN]- Al_2O_3 coatings. Dhananchezian et al. [12] studied the impact of F_c, temperature, R_a and tool wear during turning process of 2205 DSS under dry and cryogenic cooling condition. Turning with cryogenic cooling reduced the F_c, temperature, R_a and tool wear when compared with dry turning. Components of F_c are found to be decreased with increase of cutting speed in both machining conditions. They found that F_c values are decreased with increase in cutting speed in both the cutting conditions. Suresh et al. [13] studied the impact of machining parameters on R_a and F_c in turning of 2205 DSS using carbide tool coated with TiN. Their results revealed that increase in depth of cut and feed rate increases F_c, whereas increase in cutting speed decreases F_c.

Machining with low feed rate and high cutting speed resulted lower values of F_c. Sonawane and Sargade [14] investigated the machinability of DSS 2205 by employing TiC inserts coated with AlTiCrN and AlTiN. The reduction of F_c was higher for AlTiCrN coated inserts because of lower coefficient of friction. Higher speed and lower feed combination resulted minimum F_c.

From the review of literatures, it is found that very limited works are reported with respect to cutting force in the turning process of cast nitrogen alloyed duplex stainless grades. But F_c is a key parameter to evaluate the performance of turning operation. It is used in machine design and power calculation. Machining with coated tools improve the machining performance of DSS in dry turning process. Dry turning process eliminates the negative aspects of wet turning and leads to green and sustainable manufacturing. So in the current study, dry turning tests have been carried out using TiCN-Al_2O_3-TiN coated TiC tools to ascertain the impact of feed rate and cutting speed on the cutting force of cast nitrogen alloyed DSS alloy grades 5A and 4A.

2. Experimental Details

In this study 5A and 4A DSS alloys were chosen as work materials. The diameter of the DSS rod was 90 mm and length was 300 mm. The mechanical properties and composition of the material are presented in Tables 1 and 2.

Table 1. Mechanical properties of grade 5A and 4A DSS.

Property	4A DSS	5A DSS
Yield Strength (MPa)	545	595
Tensile Strength (MPa)	730	740
Hardness (BHN)	212	223
Elongation (%)	30	32

Table 2. Chemical composition of 4A and 5A DSS (Wt %).

Element	4A DSS	5A DSS
Cr	22.150	25.100
Ni	5.650	6.650
Mo	3.300	4.150
C	0.028	0.028
Si	0.650	0.670
Mn	0.710	0.870
S	0.006	0.005
P	0.027	0.028
N	0.180	0.250
Fe	Balance	Balance

Kirloskar make lathe was used for performing dry turning tests. The turning tests were conducted by using TiCN-Al_2O_3-TiN coated TiC cutting tool inserts. The specifications of Taegu Tec make tool insert used in the experiment is SNMG 120408 MT TT5100.The turning process was continuous in nature. Feed rate (f) and cutting speed (V) were the cutting variables chosen in the study. Three feeds (0.08, 0.10 and 0.12 mm/rev) and five cutting speeds (80, 100, 120, 140 and 160 m/min) were employed in the experiment. The value of depth of cut (d) employed in the turning operation was 0.5 mm. Cutting force was chosen as the output parameter. F_c was measured by employing Kistler dynamometer. The test set up is illustrated in Fig. 1. The Kistler dynamometer, data analysis and display system are shown in Figs 2 and 3, respectively.

Fig. 1. Experimental setup.

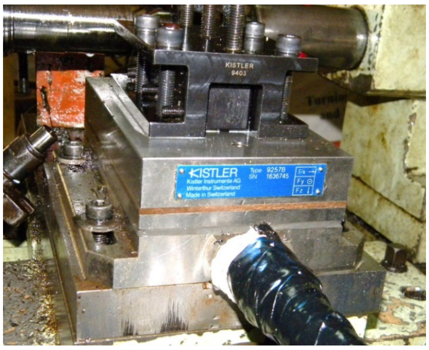

Fig. 2. Kistler dynamometer.

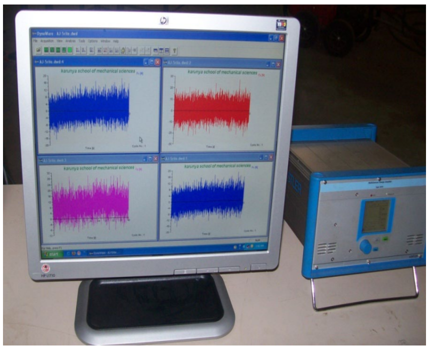

Fig. 3. Display system.

3. Results and Discussions

The work piece is machined by varying cutting parameters and the values of F_c were measured. Measured values of the F_c are given in Table 3.

Table 3. Experimental results for F_c of 4A and 5A grade DSS.

Exp. No.	*V* (m/min)	*f* (mm/rev)	*Fc* (*N*)	
			4A grade	5A grade
1	80	0.04	33.2	44.5
2	100	0.04	28.2	36.9
3	120	0.04	25.7	35.2
4	140	0.04	26.5	36.1
5	160	0.04	31.9	41.2
6	80	0.08	39.3	53.6
7	100	0.08	34.4	44.1
8	120	0.08	28.8	38.7
9	140	0.08	33.8	41.9
10	160	0.08	38.5	47.5
11	80	0.12	45.8	58.9
12	100	0.12	38.1	50.9
13	120	0.12	35.6	46.5
14	140	0.12	37.7	50.2
15	160	0.12	43.4	53.7

3.1. Impact of cutting velocity on F_c

The impact of cutting speed on F_c of two DSS alloys are depicted in Figs. 4 and 5. Up to 120 m/min cutting speed, the value of cutting force decreased with increase in cutting speed and beyond that it was increasing with increase in cutting speed. For lower cutting speeds, the F_c values are increased because of the higher friction generated by the tool-chip interaction and increase in built up edge formation. The heat generated is larger at higher cutting speeds resulted the material become soft at cutting zone. So at higher cutting speeds lower values of F_c are required. These results are well agreed with the findings of Suresh et al. [13] and Thakur et al. [15]. This trend was changed with further increase of cutting speeds (140 and 160 m/min). At these cutting speeds, cutting force values were increasing. The reason was because of higher wear rate of tool at these cutting speeds. It is determined that minimum force during turning was obtained at the cutting speed of 120 m/min.

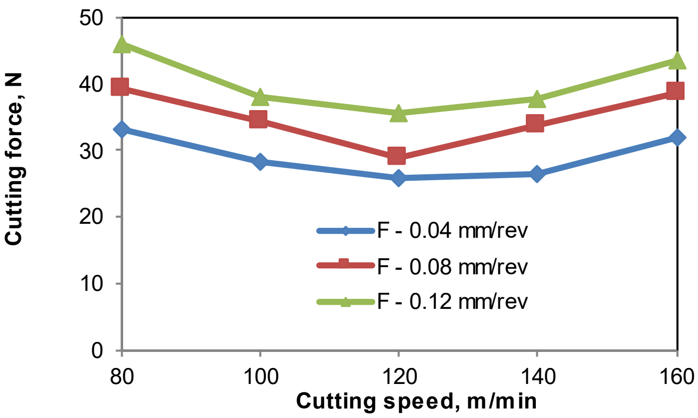

Fig. 4. Cutting speed vs. F_c of 4A DSS.

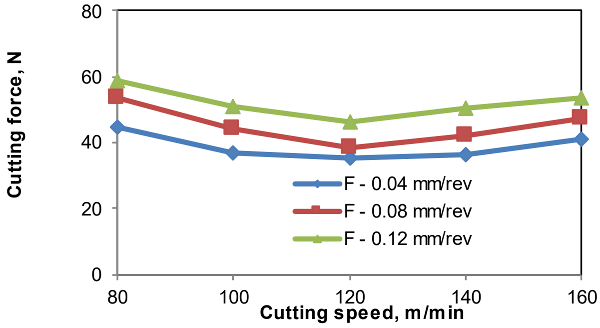

Fig. 5. Cutting speed vs. F_c of 5A DSS.

3.2. Impact of feed rate on F_c

For dry turning operation, the impact of feed rate on the F_c of two DSS alloys are depicted in Figs. 6 and 7 for five different cutting speeds. It is found that the value of F_c was raised with increase in feed rate. When the feed rate increases, the tool and work contact area and material removal rate increases. Hence, higher cutting forces are needed to remove the material. This result is well agreed with the results reported by Suresh et al. [13]. The lowest value of F_c was obtained at a feed of 0.04 mm/rev.

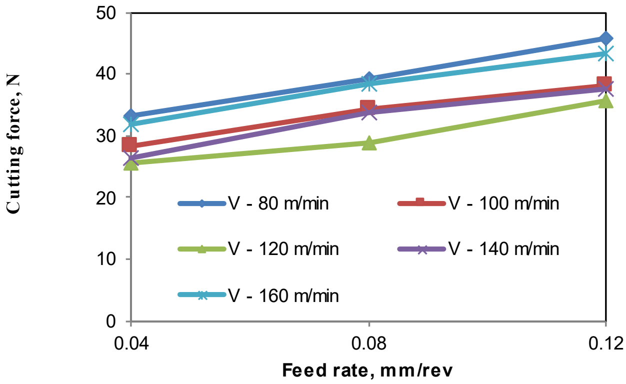

Fig. 6. Feed rate vs. F_c of 4A DSS.

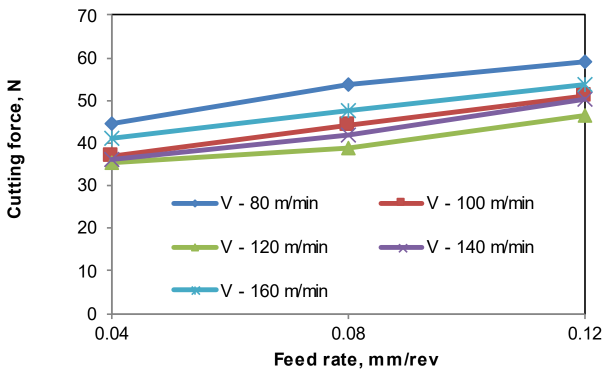

Fig. 7. Feed rate vs. F_c of 5A DSS.

3.3. Impact of grade of work piece on F_c

The F_c values are compared in Fig. 8 for the two DSS alloys. It is observed that the F_c values obtained for 4A DSS alloy are lower compared with 5A DSS alloy. The variation in the chemical compositions of both the alloys is the main reason for this difference. The variation of presence of Ni, Mo and Cr is more significant in this case. Ni, Mo and Cr content in 5A DSS are 6.65 %, 4.15 % and 25.10 %, respectively comparing to 5.65 %, 3.30 % and 22.15 % for 4A DSS alloy. Increase of Ni, Mo and Cr content increases the strength and hardness. This increasing strength and hardness resulted difficulties in machining. Similar observation was reported for 2507 SDSS by Rajaguru and Arunachalam [11]. Hence higher F_c values are needed for machining 5A DSS alloy.

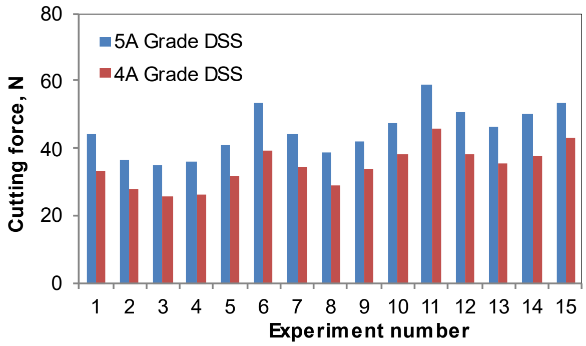

Fig. 8. Comparison of F_c between 4A and 5A grade DSS.

In the present work, five levels of cutting speeds (80,100,120,140 and 160 m/min), three levels of feed rates (0.08, 0.10 and 0.12 mm/rev) and a constant depth of cut (0.5 mm) are employed. The use of lower depth of cut resulted lower cutting force values in the order of 26 to 59 N. Dhananchezian et al. carried out turning tests for 2205 DSS. They employed three levels of cutting speeds (72, 119, 197 m/min), constant feed rate (0.111 mm/rev) and constant depth of cut (1 mm) in the dry turning operation. The cutting speeds and feed rate employed are more or less equal in both the work, but higher depth of cut was employed in their work compared to the present work. So the cutting force values obtained are higher in the order of 216 N to 255 N [12].

The hardness values of 4A and 5A DSS alloys used in the present work are in the range of 212 to 223 BHN whereas the hardness values of 2205 DSS alloy as per standards are in the range of 264 to 290 BHN. Hence, lower cutting force values are obtained in the present work.

4. Results and Discussion

Dry turning tests were carried out on DSS alloys by employing carbide tools. The impact of feed, cutting speed and grade of work piece on F_c were investigated. The conclusions are summarized as follows.

- The value of F_c reduced with the rise in cutting speed up to 120 m/min and beyond that F_c values are increased. Higher tool wear is reason for the higher values of F_c at higher cutting velocities.

- Lower values of F_c are required at lower feed compared with higher feed. Increase in tool work contact area and material removal rate are the reasons for higher values of F_c at higher feed rates.
- The lowest F_c value is obtained at a feed of 0.04 mm/rev and 120 m/min speed of cutting.
- Higher values of F_c are needed for cutting of 5A DSS than 4A DSS alloy due to higher % of Cr, Mo and Ni content.

Nomenclatures

d	Depth of cut, mm
f	Feed rate, mm/rev
F_c	Cutting force, N
R_a	Surface roughness, µ
V	Cutting speed, m/min

Symbols

Al_2O_3	Aluminum Oxide
AlTiCrN	Aluminum Titanium Chromium Nitride
AlTiN	Aluminum Titanium Nitride
TiC	Titanium Carbide
TiCN	Titanium Carbonitride
TiN	Titanium Nitride
TiOCN	Titanium (II) Oxide Carbonitride

Abbreviations

ASS	Austenitic Stainless Steel
BHN	Brinell Hardness Number
CNC	Computer Numerical Control
DSS	Duplex Stainless Steel
MT	Medium Temperature
RSM	Response Surface Methodology
SDSS	Super Duplex Stainless Steel
SS	Stainless Steel

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