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Influence of Cutting Parameters on Machinability of DSS 2205 and SDSS 2507 Materials During Milling

Pradeep George, Karunya Institute of Technology and Sciences, India
Leo Dev Wins K., Karunya Institute of Technology and Sciences, India*
D. S. Ebenezer Jacob Dhas, Karunya Institute of Technology and Sciences, India
Pramod George, Karunya Institute of Technology and Sciences, India
B. Anuja Beatrice, Sri Krishna Arts and Science College, India

ABSTRACT

Duplex and super duplex materials possess the properties of both Austenite and Martensitic steels. Properties like hardness and toughness are very high for duplex grades and are difficult to machine. In this study, machining performance of duplex stainless steel (DSS 2205) and super duplex stainless steel (SDSS 2507) were estimated during CNC dry milling operation. Cutting parameters, namely feed rate, spindle speed, and depth of cut, were considered for this investigation and were optimized by considering surface roughness, cutting force, and cutting temperature during CNC milling using Taguchi technique. Results revealed that depth of cut has more effect on cutting force than spindle speed and feed rate. Surface roughness was more influenced by feed rate than spindle speed and least influenced by depth of cut for both the materials. Results also showed that cutting temperature is mainly influenced by spindle speed. Optimum value for all the responses was obtained at spindle speed of 4200 rpm, feed rate of 50 mm/min, and depth of cut of 0.35 mm for both DSS 2205 and SDSS 2507.

KEYWORDS

ANOVA, Cutting Force, Cutting Temperature, Duplex Stainless Steel, Milling, Signal-to-Noise Ratio, Super Duplex Stainless Steel, Surface Roughness

1. INTRODUCTION

Duplex stainless steel is a type of stainless steel which contains both ferritic and austenitic phases in approximately equal proportions. DSS 2205 contain 22% chromium, 3% molybdenum and 5% nickel. Due to its high toughness and strength, it can replace thick sections of parts made up of austenitic stainless steel (ASS). DSS and SDSS materials possess high corrosion resistance qualities, especially against pitting corrosion and stress corrosion. SDSS 2507 contains 25% chromium, 6.5% Nickel and 3.5% Molybdenum. SDSS 2507 possess higher corrosion resistance and strength compared to DSS 2205. Both the materials are considered to be cost effective when compared to ASS. It is appropriate

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*Corresponding Author

to use these materials within 50 to 300° C. After 300° C, the property of the materials changes and become brittle. SDSS 2507 have high proof strength compared to DSS and ASS materials. Physical and mechanical properties of DSS 2205 and SDSS 2507 are excellent.

SDSS 2507 can be used in petroleum, hydropower, pressure vessels, pulp & paper making industries, structural components and chemical tankers. DSS 2205 has variety of applications in offshore oil and gas industries for pipe work systems and in petrochemical industries in the form of pipelines, pressure vessels, chemical processing and storage equipment. Even though duplex materials have enormous applications especially due to its exceptional non-corrosive characteristics, studies on duplex materials especially super duplex material is less compared to other materials. Previous studies report mainly turning of duplex steels. But reports on CNC milling of SDSS 2507 and DSS 2205 materials are very less mainly due to the difficulty in machining such materials.

Barbara (2014) compared the corrosion behaviour and economical aspects of different stainless steels namely Ferritic grade AISI 430, Austenitic grades AISI 304, AISI 316 along with DSS 2205 duplex grade. Results revealed that, duplex steel can be used without coating due to its high corrosion resistance, which reduces the maintenance cost. Rajguru & Arunachalam (2021) conducted experiments on SDSS material for finding out the stress corrosion cracking. It was found that, SDSS material is a good choice for marine applications due to the exceptional corrosion resistance. They also found the development of machining stresses, due to biaxial tensile residual stresses induced in the work material. This is mainly due to the selection of improper cutting parameters. To avoid this defect, proper selection of cutting parameters is inevitable.

Rajaguru & Arunachalam (2020) investigated stress corrosion cracking resistance (SCC) and machinability of SDSS under distinct cutting fluid application methods. Effect of flood cooling, dry machining and minimum quantity lubrication technique on cutting performance was analysed. Flank wear, surface finish, cutting force, chip morphology and residual stress were considered as performance indicators. It was found that low surface crack density could be achieved with MQL technique.

Gowthaman et al. (2020) reviewed the machining behaviour of DSS. The review results indicated that, machining behaviour of DSS is tough because of its higher rate of strain hardening, improved strength, Built-up edge formation, lack of thermal conductivity and fracture toughness. The work also recommends the need for coated inserts with higher toughness, sharp cutting edges with positive chip breaker and exclusion of excessive cutting speed to avoid Built-up edge formation. Nomani et al. (2013) conducted machinability tests on SDSS 2507 and DSS 2205 materials during drilling process by keeping 316L austenite steel as a reference. Flank wear, surface finish and cutting force were analysed and compared under similar cutting conditions. Both SDSS 2507 and DSS 2205 materials revealed poor machinability responses and flute damage were observed on the drill bit with built-up edge formation. Drilling of SDSS 2507 revealed poorer surface finish and higher cutting force compared to the other two steels (DSS 2205 and 316L ASS).

Rajaguru & Arunachalam (2017) investigated the behaviour of four different PVD and CVD coated tools during dry turning of SDSS material. Cutting tool performance was analysed by considering surface integrity, tool wear, cutting force and cutting temperature. Results revealed that [MT-TiCN]-Al_2O_3 coated tool can provide better wear resistance along with better surface finish compared to other coated tools.

Paulo Davim & Luis (2007) conducted dry turning experiments on tool steel with hardness of 60 HRC to study the machinability. The impact of parameters on tool wear, surface finish and cutting pressure was evaluated with ANOVA analysis. Ceramic cutting tool was utilized for the machining of hardened tool steel D2. It was found that cutting velocity had high impact on the tool wear. Feed rate and cutting time had high influence on surface finish. Feed rate had large effect on cutting pressure. Results revealed that, appropriate selection of cutting parameters can achieve improved surface finish which can avoid finish grinding after turning process.

Paulo Davim & Pedro (2005) conducted experiment to realize the impact of cutting parameters on surface finish and the destruction in laminate plates of composite material (CFRPs) during end milling operation. Experiment was conducted with two types of cutting tools (2 flute and 6 flute end mill) by considering cutting velocity and feed rate as machining parameters. Experiment was conducted with L_9 orthogonal array and cutting attributes were analysed by ANOVA. Results revealed a decrease in surface finish with the rise in feed rate and reduction in cutting speed for both the end mills. The 6-flute end mill generated more destruction on the laminate than the 2-flute end mill. Experimental results also revealed that feed rate has higher impact on the surface finish than cutting velocity for both the cases. Vinoth et.al (2017) conducted a review on machining and other allied operations on DSS 2205 material. Machinability of DSS 2205 was compared with that of ASS 304L and 316. It was found that the machinability of DSS 2205 was less than ASS materials. However, surface roughness of DSS 2205 was higher, which enables the usage of DSS in costal applications.

Paulo et al. (2020) studied the machinability of duplex steels during milling operation using aluminium titanium nitrite coated inserts by comparing conventional milling strategy with trochoidal strategy. Cutting speed ranges of 90 to 120 m/min and 120 to 300 m/min were selected for the conventional and trochoidal strategies respectively. It was observed that, damage of tool edge was caused mainly by the gradual growth of wear on the flank surface followed by chipping. Best results were attained at a cutting velocity of 120 m/min with MRR of 17.16 cm^3/min for conventional milling approach and 240 m/min with high MRR of 23.66 cm^3/min for trochoidal approach with a constant tool life of 20 min. Philip (2017) used Taguchi technique for optimizing process parameters during milling of hard to machine 5A grade DSS material. Feed rate, spindle speed and axial depth were considered for the investigation. Results indicated that cutting force is largely influenced by feed rate. Optimum cutting force could be attained with higher values of spindle speed with lower values of axial depth and feed rate.

Jay et al. (2018) analysed machined surface quality during milling of SDSS 2507 under dry and wet cutting environments. Multiple regression analysis was used to attain the correlation between surface finish and machining parameters. The analysis indicated that feed rate has larger impact on surface finish followed by the cutting velocity. Krolczyk et al. (2017) studied the effect cutting conditions on machining performance during turning of DSS under wet and dry cutting conditions. Three different carbide tools were used. The results showed that dry turning with the appropriate grade of cutting tool can achieve three-fold enhancement in tool life in contrast to the machining with cutting fluids. It was also observed that, combination of lesser values of feed rate, larger values of cutting speed with dry cutting condition reduce the energy consumption. Yang & Tarng (1998) used Taguchi method to identify the optimal parameter during machining operation. They have analysed the machining characteristics of steel bar using S/N ratio and ANOVA.

Pramod & Philip (2021) conducted experiments on MSS grades 410 and 420 to identify the impact of cutting parameters on surface finish during CNC dry milling. A constant axial depth with varying feed rate and speed were considered as input variables. Experiments were conducted as per the L_9 OA. ANOVA results revealed that cutting speed has more impact on surface finish than feed rate for both materials. Optimized results were compared with predicted results, and the model was found to be adequate.

Previous researchers mainly focused on turning, drilling and welding of duplex steels. Comparison of duplex steels with Austenitic stainless steels and Martensitic steels was also focused by few researchers, but comparative studies between super duplex stainless steels with other materials are very limited. SDSS and DSS materials have wide range of applications but they are difficult to machine because of their exceptional hardness. Machinability studies related to duplex steels are less in many areas especially in milling of duplex stainless steel and super duplex stainless steels. Studies on milling of SDSS 2507 and DSS 2205 materials are limited and they are not properly analysed by previous research works. Hence, behaviour of SDSS 2507 and DSS 2205 materials during milling operation need to be more focused. When compared to other materials, DSS and SDSS materials have good resistance to corrosion along with good crack resistance even these materials are exhausted to chemical environments. Utilization of these materials must be increased more in industrial fields due to their good qualities. So, optimization and evaluation of machining performance of super duplex stainless steel and duplex steels are needed especially for CNC milling operation.

From the literature survey it is clear that limited work is reported on conventional milling of SDSS 2507 and DSS 2205 materials. But no work is reported on the optimization of machining parameters during high speed CNC end milling SDSS 2507 and DSS 2205 materials and their comparison, which is needed for the better use of these materials in different applications. Due to the lack of information in this field, it is important to optimize the cutting parameters. This paper is mainly focused on finding out optimum cutting parameters during high speed CNC dry milling of DSS 2205 and SDSS 2507 materials. It is also decided to compare the machinability of both the materials.

1.1 Nomenclature

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

1.2 Abbreviations

MSS: Martensitic stainless steel
ASS: Austenitic stainless steel
BUE: Built up edge
HRC: Rockwell hardness measured in C scale
HPT: High pressure torsion test
DSS: Duplex Stainless Steel
SDSS: Super Duplex Stainless Steel
RSM: Response surface methodology
TiC: Titanium Carbide
TiCN: Titanium Carbo Nitride
SNR: Signal to Noise ratio
ANOVA: Analysis of Variance

2. TAGUCHI TECHNIQUE

Taguchi method (Taguchi, 1990) is considered to be one of the important techniques used for getting optimized design with the support of product and process design. It is also called factorial design of experiments as most of the Taguchi designs are related to factorial designs. Taguchi technique significantly decreases costs and time required for the design of experiment otherwise huge number of experiments need to be conducted and evaluated. Quality loss function is applied to identify the variation between the obtained result and target performance.

3. EXPERIMENTATIONS

3.1 Work Material Selection

Work materials selected for the research work are SDSS 2507 and DSS 2205. Table 1 and Table 2 shows chemical composition and mechanical properties of materials respectively selected for CNC milling operation. Rectangular blocks of work materials with dimensions of 100 mm × 80 mm × 50 mm were used.

Table 1. Chemical composition of DSS 2205 and SDSS 2507

Alloy	Cr	Ni	Mo	C	N	Mn	Si	P	S	Fe
DSS 2205	22.45	5.265	3.081	0.028	0.137	1.632	0.451	0.026	0.006	Balance
SDSS 2507	25.38	6.637	3.658	0.024	0.284	0.657	0.370	0.024	0.004	Balance

Table 2 Mechanical properties of DSS 2205 and SDSS 2507

Alloy	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Hardness (HRC)
DSS 2205	620	450	27	30
SDSS 2507	750	551	23	32

3.2 CNC Milling Operation

BMV 40 T20 CNC machining centre was used for performing the milling operation. The machining centre had the range of spindle speed from 60 to 6000 rpm with the spindle power rating of 10 kW. EAP 300R-16D-160L-2T-W end mill tool holder of 16mm diameter and APMT 1135PDR -YBG 205 tungsten carbide inserts with TiCN coating were used for performing the experiments. Amprobe infrared thermometer (Model IR-750) was used for measuring cutting temperature. Kistler (model 9257B) dynamometer was used for measuring the cutting force and Mitutoyo (Model SJ210) roughness tester was utilized for measuring the roughness. Dry cutting was performed. The experimental setup and the facility for cutting temperature measurement are presented in Figure 1 and Figure 2 respectively.

Figure 1. Experimental setup

Figure 2. Measurement of cutting temperature

3.3 Selection of Cutting Parameters

DSS 2205 and SDSS 2507 materials were selected for dry milling using CNC machining centre. Spindle speed, feed rate and depth of cut were identified as cutting parameters. Trial runs were conducted to detect the range of parameters. The parameters were varied in three levels and the levels of cutting parameters are presented in Table 3.

3.4 Experimental Plan

To reduce the amount of experiments, L_{27} Taguchi's orthogonal array was planned. Experiments were conducted on DSS 2205 and SDSS 2507 materials using CNC milling machine. Experimental parameters and its observations are presented in Table 4. Effect of cutting parameters on the machining performance was evaluated using ANOVA. S/N values were calculated based on "smaller-the-better" criteria.

3.5 Analysis of S/N Ratio

The S/N ratio is employed to identify the deviation of output from the desired value. The S/N ratio (η) is presented using the following equation (Yang & Tarng, 1998):

$$\eta = -10\log\left(M.S.D\right) \quad (1)$$

Table 3. Parameters and their levels

Input parameter	Level 1	Level 2	Level 3
Spindle speed (rpm)	1400	2800	4200
Feed rate (mm/min)	50	100	150
Depth of cut (mm)	0.35	0.7	1.05

Smaller-the-better quality characteristic was chosen for obtaining optimal machining performance. The following equations represent smaller-the-better quality characteristics for cutting force, surface roughness and temperature. M.S.D is mean square deviation for output characteristics (Yang & Tarng, 1998):

$$\text{M.S.D} = \frac{1}{m}\sum_{i=1}^{m} Fi^2 \quad (2)$$

$$\text{M.S.D} = \frac{1}{m}\sum_{i=1}^{m} Si^2 \quad (3)$$

$$\text{M.S.D} = \frac{1}{m}\sum_{i=1}^{m} ti^2 \quad (4)$$

In the above equations, m represent the number of tests, F_i, S_i and t_i are the values of the cutting force, surface roughness and temperature, respectively for the i^{th} test. Optimal values could be found out using the S/N equations.

3.6 Analysis of Variance

ANOVA was performed to detect the design variable that substantially affects the response. Yang and Tarng (1998) point out the total sum of squared deviations using the equation given below:

$$SS_T = \sum_{i=1}^{n} \left(\eta_i - \eta_m\right)^2 \quad (5)$$

where, n is the number of tests, η_i is the mean *S/N* ratio for the i^{th} experiment and η_m is the total mean *S/N* ratio. SS_T was generated from the sum of the squared deviations (SS_d) and the sum of the squared error (SS_e) for each design parameter.

4. RESULTS AND DISCUSSION

The experimental design was made based on Taguchi L_{27} orthogonal array (Table 4) to relate the impact of cutting parameters on surface roughness, cutting temperature and cutting force. The recorded results were analyzed using MINITAB-19 software.

Effect of cutting parameters on output responses were evaluated using ANOVA. S/N values were calculated based on "smaller-is-better" formula and it was used to measure the cutting performance statistically.

4.1 Effect of Cutting Parameters on Cutting Force (F_c)

Taguchi technique was used to evaluate the impact of cutting variables on cutting force. S/N response for cutting force is presented in tables 5 and 6. Figure 3 and Figure 4 show the main effects plots for cutting force for DSS 2205 and SDSS 2507 respectively. Analysis of variance results for both the grades of steel are given in Tables 7 and 8.

Table 4. Experimental data collected

Exp. No.	Spindle speed N(rpm)	Feed Rate f(mm/min)	Depth of cut d(mm)	Surface roughness, R_a(μm)		Temperature, T(°C)		Cutting force, F_c(N)	
				DSS 2205	SDSS 2507	DSS 2205	SDSS 2507	DSS 2205	SDSS 2507
1	1400	50	0.35	0.65	1.07	41.22	45.76	309.53	467.52
2	1400	50	0.7	0.66	1.12	52.75	57.7	327.11	486.13
3	1400	50	1.05	0.69	1.14	60.49	67.41	355.01	521.34
4	1400	100	0.35	0.78	1.13	42.78	46.11	317.51	479.94
5	1400	100	0.7	0.81	1.14	54.79	59.09	338.23	500.21
6	1400	100	1.05	0.82	1.16	61.05	71.04	369.84	539.59
7	1400	150	0.35	0.95	1.37	45.98	50.36	329.45	492.84
8	1400	150	0.7	1.00	1.39	55.97	66.01	356.91	521.43
9	1400	150	1.05	1.05	1.40	62.5	72.41	383.61	568.04
10	2800	50	0.35	0.51	0.77	47.64	52.26	301.62	451.06
11	2800	50	0.7	0.53	0.82	57.61	69.08	324.64	464.25
12	2800	50	1.05	0.59	0.90	67.68	74.25	343.82	502.03
13	2800	100	0.35	0.67	1.02	48.91	57.5	312.86	464.68
14	2800	100	0.7	0.69	1.05	58.52	69.9	346.78	495.35
15	2800	100	1.05	0.71	1.15	68.97	78.66	357.97	531.76
16	2800	150	0.35	0.89	1.23	54.61	59.66	325.17	469.32
17	2800	150	0.7	0.95	1.26	60.75	72.65	336.16	513.38
18	2800	150	1.05	0.97	1.30	71.69	79.44	377.23	551.17
19	4200	50	0.35	0.40	0.66	61.92	66.75	296.41	449.41
20	4200	50	0.7	0.42	0.72	67.74	75.17	321.77	458.44
21	4200	50	1.05	0.45	0.81	79.6	96.25	340.82	491.90
22	4200	100	0.35	0.56	1.01	72.11	77.42	308.72	461.17
23	4200	100	0.7	0.59	1.03	76.37	81.94	337.91	486.92
24	4200	100	1.05	0.61	1.07	85.21	97.43	350.75	520.74
25	4200	150	0.35	0.79	1.15	75.4	83.17	318.38	465.16
26	4200	150	0.7	0.83	1.17	81.44	94.13	331.08	506.12
27	4200	150	1.05	0.88	1.31	98.9	109.95	375.11	548.01

From the S/N ratio responses given in Table 5 and 6, it is clear that depth of cut has higher impact on cutting force. From the Figure 3 and Figure 4, maximum S/N effect is observed on the cutting force for spindle speed at level 3, rate of feed and depth of cut at level 1. Optimum value of cutting force was obtained at the spindle speed of 4200 rpm, feed rate of 50 mm/min and depth of cut of 0.35 mm for both the materials. From the ANOVA results on cutting force given in tables 7 and 8 for DSS 2205 and SDSS 2507 materials respectively, it is clear that cutting force is least affected by spindle speed. The percentage influence of depth of cut, feed rate and spindle speed on cutting force are 73.45%, 17.61% and 4.41% respectively for DSS 2205 material. For SDSS 2507 material,

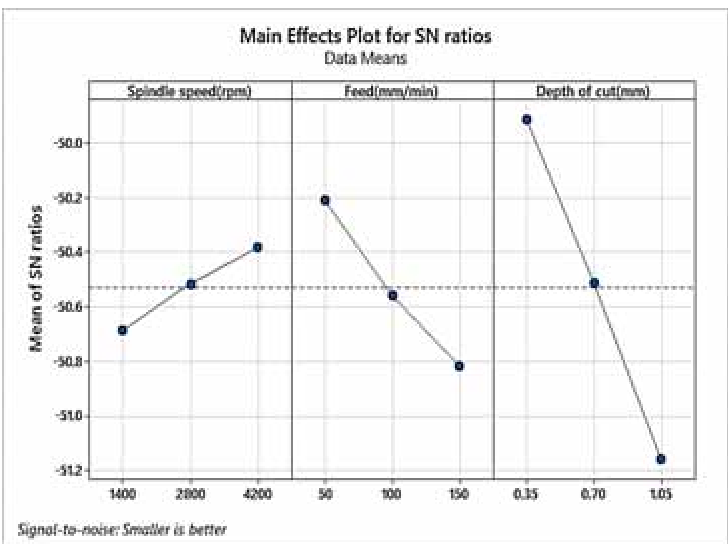
Table 5. S/N response table for cutting force (DSS 2205)

Level	Spindle speed (rpm)	Feed (mm/min)	Depth of cut (mm)
1	-50.69	-50.21	-49.91
2	-50.51	-50.56	-50.51
3	-50.38	-50.81	-51.16
Delta	0.30	0.60	1.24
Rank	3	2	1

Table 6. S/N response table for cutting force (SDSS 2507)

Level	Spindle Speed (rpm)	Feed (mm/min)	Depth of cut (mm)
1	-54.11	-53.56	-53.38
2	-53.85	-53.93	-53.84
3	-53.74	-54.22	-54.49
Delta	0.37	0.66	1.11
Rank	3	2	1

Figure 3. Main effects plot for S/N means -Cutting force (DSS 2205)



the percentage influence of depth of cut, feed rate and spindle speed on cutting force are 65.58%, 23.29% and 7.46% respectively. Results from the ANOVA tables indicate that depth of cut has more impact on cutting force. The optimal results for cutting force could be achieved during high-speed CNC end milling of DSS 2205 and SDSS 2507 materials by maintaining spindle speed at 4200 rpm, feed rate at 50 mm/min and depth of cut at 0.35 mm. Results indicated that machinability of SDSS 2507 was lower than DSS 2205 due to the presence of extra molybdenum and chromium content in SDSS 2507 which enhanced its toughness and strength. Results also indicated that depth of cut has

Figure 4. Main effects plot for S/N means - Cutting force (SDSS 2507)

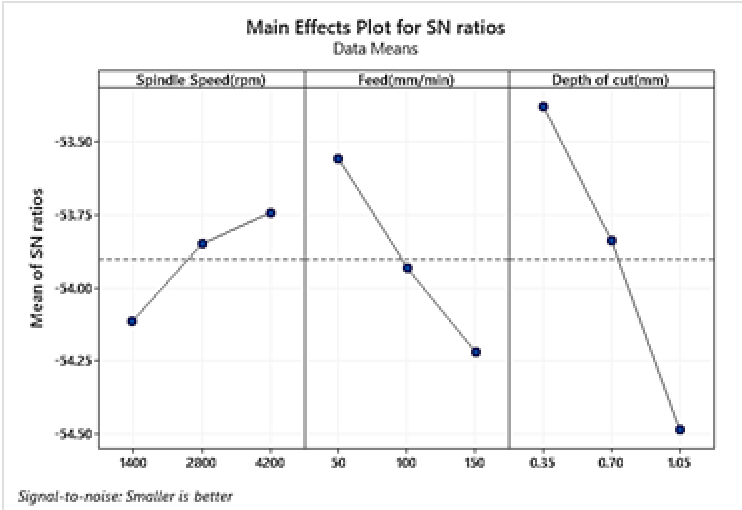


Table 7. ANOVA results on cutting force for DSS 2205 material

Source	DF	Adj SS	Adj MS	F-Value	P-value	Contribution %
Spindle speed(rpm)	2	631.7	315.85	9.74	0.001	4.41
Feed(mm/min)	2	2519.3	1259.67	38.86	0.000	17.61
Depth of cut(mm)	2	10508.6	5254.28	162.10	0.000	73.45
Error	20	648.3	32.41			4.53
Total	26	14307.9				100

Table 8. ANOVA results on cutting force for SDSS 2507 material

Source	DF	Adj SS	Adj MS	F-Value	P-value	Contribution %
Spindle Speed(rpm)	2	2103	1051.70	20.33	0.000	7.46
Feed(mm/min)	2	6571	3285.74	63.51	0.000	23.29
Depth of cut(mm)	2	18500	9250.21	178.80	0.000	65.58
Error	20	1035	51.74			3.67
Total	26	28210				100

more impact on cutting force, which showed a similar trend as reported in previous literature (Philip Selvaraj, 2017).

4.2 Effect of Cutting Parameters on Surface Roughness (R_a)

Influence of cutting parameters on surface roughness was analysed for both the materials using Taguchi technique. SNR response for average roughness (R_a) is given in tables 9 and 10. Figure5 and Figure 6 show main effects plots for surface roughness for DSS 2205 and SDSS 2507 materials respectively. Analysis of variance results for both the grades of steel are given in Tables 11 and 12.

Results from the Signal to noise ratio responses given in Tables 9 and 10, it is clear that feed rate has higher impact on surface roughness. Feed rate had larger impact on surface roughness. From the Figure 5 and Figure 6, maximum S/N effect is observed on the surface roughness for spindle speed at level 3, rate of feed and depth of cut at level 1. Optimum value of surface roughness was obtained at the spindle speed of 4200 rpm, feed rate of 50 mm/min and depth of cut of 0.35 mm for DSS 2205 and SDSS 2507. From the ANOVA results on surface roughness given in Tables 11 and 12 for DSS 2205 and SDSS 2507 materials respectively, it is clear that surface roughness is least affected by depth of cut.

Table 9. S/N response table for surface roughness (DSS 2205)

Level	Spindle speed (rpm)	Feed (mm/min)	Depth of cut (mm)
1	1.8120	5.4388	3.5252
2	3.0383	3.2557	3.1510
3	4.5687	0.7245	2.7428
Delta	2.7567	4.7144	0.7825
Rank	2	1	3

Table 10. S/N response table for surface roughness (SDSS 2507)

Level	Spindle speed (rpm)	Feed (mm/min)	Depth of cut (mm)
1	-1.6351	1.1657	-0.1972
2	-0.3317	-0.6922	-0.4953
3	0.2710	-2.1694	-1.0034
Delta	1.9061	3.3352	0.8062
Rank	2	1	3

Figure 5. Main effects plot for S/N means – surface roughness (DSS 2205)

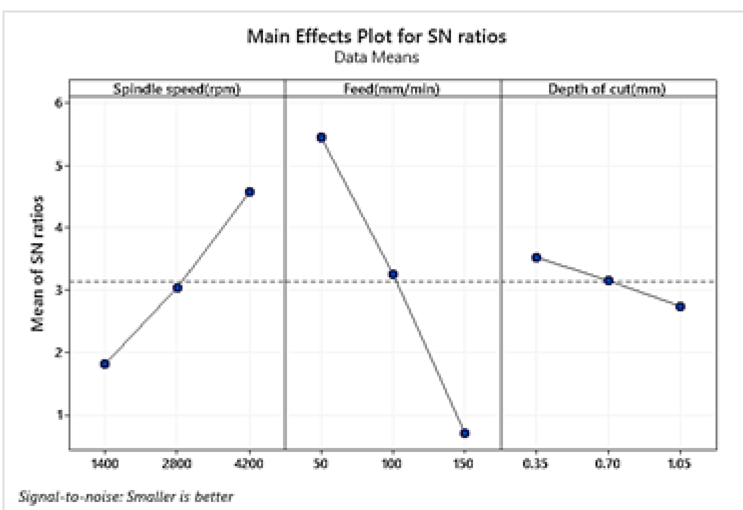


Figure 6. Main effects plot for S/N means – surface roughness (SDSS 2507)

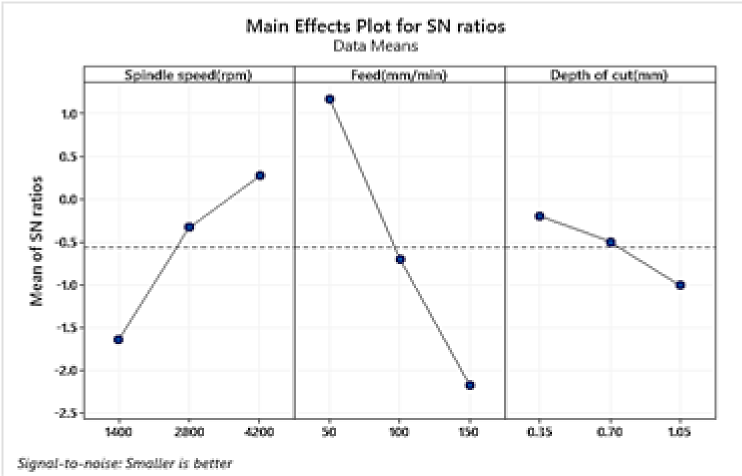


Table 11. ANOVA results on surface roughness for DSS 2205 material

Source	DF	Adj SS	Adj MS	F-Value	P-value	Contribution %
Spindle speed(rpm)	2	0.196474	0.098237	236.82	0.000	22.36
Feed(mm/min)	2	0.625874	0.312937	790.56	0.000	71.23
Depth of cut(mm)	2	0.018052	0.009026	21.76	0.000	2.05
Error	20	0.038296	0.0019148			4.36
Total	26	0.878696				100

Table 12. ANOVA results on surface roughness for SDSS 2507 material

Source	DF	Adj SS	Adj MS	F-Value	P-value	Contribution %
Spindle speed(rpm)	2	0.25139	0.125695	29.47	0.000	23.71
Feed(mm/min)	2	0.70814	0.354070	89.40	0.000	66.80
Depth of cut(mm)	2	0.03943	0.019715	4.98	0.002	3.72
Error	20	0.06121	0.0030605			5.77
Total	26	1.06016				100

The percentage influence of feed rate, spindle speed and depth of cut on surface roughness is 71.23%, 22.36%and 2.05% respectively for DSS 2205 material. For SDSS 2507 material, the percentage influence of feed rate, spindle speed and depth of cut on are 66.80%, 23.71% and 3.72% respectively. Results from ANOVA tables indicate that feed rate has more impact on surface roughness. The optimal results for surface roughness could be achieved during high speed CNC end milling of DSS 2205 and SDSS 2507 materials by maintaining spindle speed at 4200 rpm, feed rate at 50 mm/min and depth of cut at 0.35 mm. Results revealed that surface finish of SDSS 2507 is better than DSS 2205 material due to the presence of higher nickel and nitrogen content which enhanced ductility and prevents the metal from oxidation during machining. Results also indicated that feed rate has more influence on surface roughness, which showed a similar trend as reported in previous literature (Jay et al, 2018; Paulo Davim & Pedro, 2005; Paulo Davim & Luis, 2007).

4.3 Effect of Cutting Parameters on Cutting Temperature

Influence of cutting variables on cutting temperature was analysed using Taguchi technique. S/N ratio response for cutting temperature is given in Tables 13 and 14. Figure 7 and Figure 8 show main effects plots for cutting temperature for DSS 2205 and SDSS 2507 materials respectively. Analysis of variance results for both the grades of steel are given in Tables 15 and 16.

Results from the Signal to noise ratio responses given in Tables 13 and 14, it is clear that spindle speed has larger impact on cutting temperature. Cutting temperature is mainly affected by spindle speed. From the Figure 7 and Figure 8, maximum S/N effect is observed on the cutting temperature for spindle speed, rate of feed and depth of cut at level 1. Optimum value of cutting temperature was obtained at the spindle speed of 1400 rpm, feed rate of 50 mm/min and depth of cut of 0.35 mm for DSS 2205 and SDSS 2507. From the ANOVA results on cutting temperature given in tables 15 and 16 for DSS 2205 and SDSS 2507 materials respectively. It is clear that cutting temperature is least affected by feed rate.

The percentage influence of spindle speed, depth of cut and feed rate on cutting temperature are 59.15%, 30.96% and 5.63% respectively for DSS 2205 material. For SDSS 2507 material, the percentage influence of spindle speed, depth of cut and feed rate on cutting temperature are 53.60%, 36.51% and 5.90% respectively. Results from the ANOVA tables indicate that spindle speed has more impact on cutting temperature.

The optimal results for cutting temperature could be achieved during CNC end milling of DSS 2205 and SDSS 2507 materials by maintaining spindle speed at 4200 rpm, feed rate at 50 mm/min and depth of cut at 0.35 mm. Temperature developed during milling of DSS 2205 was less compared to that of SDSS 2507 material due to the existence of larger nitrogen and nickel content which increases melting point of SDSS 2507. Results also indicated that spindle speed has more influence on cutting temperature, which showed a similar trend as reported in previous literature (Jay et al, 2018; Paulo Davim & Luis, 2007).

Table 13. S/N response table for cutting temperature (DSS 2205)

Level	Spindle Speed (rpm)	Feed (mm/min)	Depth of cut(mm)
1	-34.40	-35.36	-34.54
2	-35.42	-35.83	-35.88
3	-37.73	-36.37	-37.14
Delta	3.33	1.01	2.61
Rank	1	3	2

Table 14. S/N response table for cutting temperature (SDSS 2507)

Level	Spindle Speed (rpm)	Feed (mm/min)	Depth of cut (mm)
1	-35.37	-36.36	-35.36
2	-36.59	-36.84	-37.02
3	-38.69	-37.45	-38.27
Delta	3.31	1.09	2.90
Rank	1	3	2

Figure 7. Main effects plot for S/N means – cutting temperature (DSS 2205)

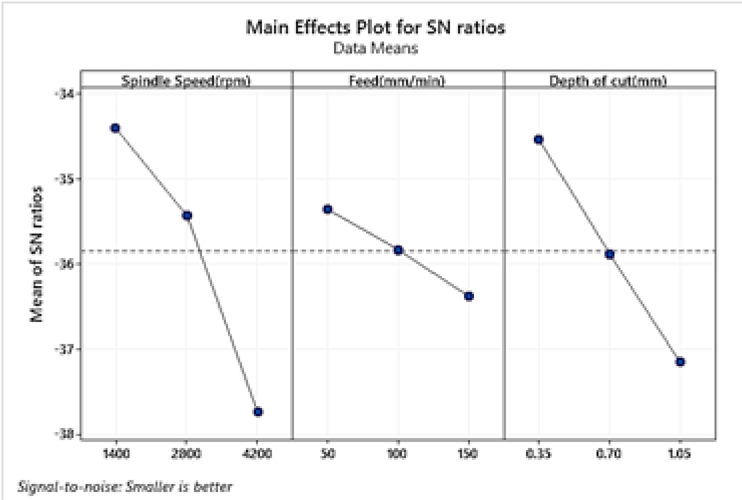


Figure 8. Main effects plot for S/N means – cutting temperature (SDSS 2507)

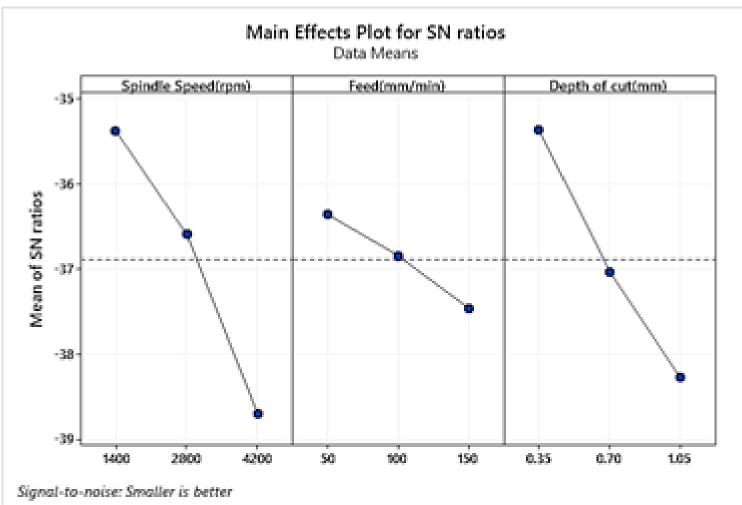


Table 15. ANOVA results on cutting temperature for DSS 2205 material

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution %
Spindle Speed (rpm)	2	2915.5	1457.77	138.94	0.000	59.15
Feed (mm/min)	2	277.6	138.80	13.23	0.000	5.63
Depth of cut (mm)	2	1526.1	763.05	72.73	0.000	30.96
Error	20	209.8	10.49			4.26
Total	26	4929.1				100

Table 16. ANOVA results on cutting temperature for SDSS 2507 material

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution %
Spindle Speed (rpm)	2	3525.1	1762.56	134.30	0.000	53.60
Feed (mm/min)	2	387.9	193.93	14.78	0.000	5.90
Depth of cut (mm)	2	2400.7	1200.33	91.46	0.000	36.51
Error	20	262.5	13.12			3.99
Total	26	6576.1				100

4.4 Effect of Work Piece Material Properties on Surface Roughness and Cutting Force

The relative machinability of DSS material is poor because of its high tensile strength and high yield point. This is due to existence of high chromium content and other constituents in material. In this study CNC milling of DSS 2205 and SDSS 2507 materials were taken for experimentation. Effect of cutting variables on surface roughness, cutting force and cutting temperature during milling of DSS 2205 and SDSS 2507 materials were analyzed. While comparing the experimental results obtained during the CNC milling of DSS 2205 and SDSS 2507 materials, (Tables 17 and 18), it is clear that, the values obtained for surface roughness, cutting force and cutting temperature are higher for super duplex material. This is because of the variation in chemical composition of duplex and super duplex material. Percentage composition of Chromium and Molybdenum for DSS 2205 material is 22.45% and 3.01% respectively while the percentage composition of Chromium and Molybdenum for SDSS 2507 material is 25.38% and 3.7%. Due to excessive chromium content in SDSS 2507 material, hardness and strength of SDSS 2507 material is higher.

Presence of extra molybdenum content in SDSS 2507 improves its toughness and strength. Presence of nickel and nitrogen enhance ductility, increases melting point and prevent the metal from oxidation during operation. Due to the enhancement in constituent percentages, cutting force, surface roughness and cutting temperature values are higher for SDSS 2507 material compared with DSS 2205 material. Table 17 shows the cutting force and surface roughness values under optimum cutting conditions. Table 18 shows the cutting temperature values under optimum cutting conditions.

5. CONCLUSION

In this study, machining performance of Duplex Stainless Steel (DSS 2205) and Super Duplex Stainless Steel (SDSS 2507) was estimated during high speed CNC dry milling operation. Cutting parameters namely feed rate, spindle speed and depth of cut were considered for this investigation and were optimized by considering surface roughness, cutting force and cutting temperature during high speed CNC milling using Taguchi technique. Based on the experimental results, following conclusions were arrived:

Table 17. Cutting force and surface roughness values at optimum cutting conditions

Spindle speed, N(rpm)	Feed rate, f (mm/min)	Depth of cut d (mm)	Surface roughness R_a (μm)		Cutting force F_c (N)	
			DSS 2205	SDSS 2507	DSS 2205	SDSS 2507
4200	50	0.35	0.40	0.66	296.41	449.41

Table 18. Cutting temperature values at optimum cutting conditions

Spindle speed, N (rpm)	Feed rate, f (mm/min)	Depth of cut (mm)	Temperature °C	
			DSS 2205	SDSS 2507
1400	50	0.35	41.22	45.76

- The optimal results for cutting force could be achieved during high speed CNC end milling of DSS 2205 and SDSS 2507 materials by maintaining spindle speed at 4200 rpm, feed rate at 50 mm/min and depth of cut at 0.35 mm. It is evident that depth of cut has higher impact on cutting force.
- Optimum value of surface roughness was obtained at the spindle speed of 4200 rpm, feed rate of 50 mm/min and depth of cut of 0.35 mm for both DSS 2205 and SDSS 2507. Results revealed that feed rate has higher impact on surface roughness.
- Also, optimum value of cutting temperature could be achieved at the spindle speed of 1400 rpm, feed rate of 50 mm/min and depth of cut of 0.35 mm for both DSS 2205 and SDSS 2507. Results showed that spindle speed has greater impact on cutting temperature.

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CONFLICT OF INTEREST

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AUTHOR CONTRIBUTIONS

Pradeep George: Conceptualization, Methodology, Data curation
K. Leo Dev Wins: Supervision, Reviewing
D.S. Ebenezer Jacob Dhas: Validation, Editing
Pramod George: Reviewing and Editing
B. Anuja Beatrice: Reviewing and Validation.

AVAILABILITY OF DATA AND MATERIAL

Data not available due to [ethical/legal/commercial] restrictions.

COMPLIANCE WITH ETHICAL STANDARDS

This research work, complies with all the necessary ethical standards required for publishing.

CONSENT TO PARTICIPATE

Not applicable.

CONSENT FOR PUBLICATION

All authors hereby provide their consent for publication in this journal.

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Pradeep George was born in Kerala, India. He received his Bachelor's degree in Mechanical Engineering from CUCEK, Cochin university in 2004 and Master's degree in Mechanical Engineering from Government Engineering College, Thrissur, Calicut University in 2008 from India. He is currently a Research Scholar in Karunya Institute of Technology and Sciences (KITS), Coimbatore, India. His areas of Interest are machining of special grade metals and its cutting parameter estimation. Mr. Pradeep George is an Associate Member of Institution of Engineer's, India (IEI) and Life member of Indian Society of Technical Education (ISTE). He has published 4 papers in International Journals. He has more than 11 years of teaching experience in Mechanical engineering department.

K. Leo Dev Wins is currently working as professor, in the department of mechanical engineering, Karunya Institute of Technology and Sciences, Coimbatore. He has published more than 50 papers in reputed international journals and international conferences. His main research interests are machining studies on steel and composites, machining with minimal cutting fluid application, machine vision, and soft computing. He has more than 23 years of teaching and research experience.

D.S. Ebenezer Jacob Dhas is Assistant professor in the department of mechanical engineering at Karunya Institute of Technology and Sciences, Coimbatore. He has completed his PhD in the area of machining and corrosion studies of composites. He has published 10 papers in reputed international journals and presented 8 papers in international conferences.

Pramod George was born in Kerala, India. He received his Bachelor's degree in Mechanical Engineering from CUCEK, Cochin university in 2004 and Master's degree in Mechanical Engineering from Government Engineering College, Thrissur, Calicut University in 2008 from India. He is currently a Research Scholar in Karunya Institute of Technology and Sciences (KITS), Coimbatore, India. His areas of Interest are Machining of special grade metals and its cutting parameter estimation. Mr. Pramod George is an Associate member of Institution of Engineer's, India (IEI) and Life member of Indian Society of Technical Education (ISTE). He has published 5 papers in International Journals.

B. Anuja Beatrice is currently working as Associate Professor in the Department of Computer Science, Sri Krishna Arts and Science College, Coimbatore, Tamilnadu, India. She has got 20 years of teaching and research experience. She has published 20 papers in reputed journals and conferences. Her areas of expertise are soft computing and data mining.