Optimization of CNC Dry Milling Parameters for MSS 410 and MSS 420 Using Taguchi Method: A Comparative Study on Machining Temperature

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Abstract: The experimental study focuses on the optimization of CNC dry milling parameters for AISI 410 stainless steel and AISI 420 stainless steel with respect to machining temperature using the Taguchi Method. An L9 orthogonal array was adopted with three levels of cutting parameters: spindle speed (1000–2000 rpm), depth of cut (0.3–0.9 mm) and constant Feed rate 60mm/min to systematically evaluate their influence under dry milling conditions. Taguchi response analysis based on mean values indicates that depth of cut is the most influential parameter affecting temperature (Rank 1), followed by spindle speed (Rank 2) and feed rate (Rank 3) for both materials. The results show a consistent increase in temperature with increasing levels of cutting parameters, with depth of cut contributing most significantly due to enhanced material removal rate and frictional heat generation at the tool–workpiece interface. A comparative evaluation reveals that both MSS 410 and MSS 420 exhibit similar thermal behavior trends; however, MSS 420 records slightly higher temperature values under identical machining conditions. This is attributed to its higher hardness, which results in increased cutting resistance and greater heat generation during machining. The optimal machining condition for minimizing temperature is identified as a spindle speed of 1000 rpm, depth of cut of 0.3 mm and feed rate of 60 mm/min, and for both materials. The close agreement between predicted and experimental results validates the effectiveness of the Taguchi approach in optimizing machining parameters.

Keywords: *Martensitic stainless steel, CNC dry milling, machining temperature, AISI 410, AISI 420, Taguchi method, cutting parameters, optimization.*

1. INTRODUCTION

Martensitic stainless steels (MSS) are similar to low alloy or carbon steels, with chromium as the principal alloying element, typically present at 12-15%. Among the MSS family, grades 410 and 420 contain a chromium at 11.5-13.5%, together with iron, manganese, carbon and other trace elements. MSS 410 is regarded as a normal purpose grade with a maximum chromium content of about 12%, while MSS 420 offers greater hardness and strength along with corrosion resistance comparable to MSS 410. AISI 410 grade MSS is widely used in the production of petroleum fractionating equipment, shafts, pumps, valves, steam and gas turbine blades and buckets, as well as cutlery. Similarly, AISI 420 grade is

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commonly employed in the manufacture of shear blades, needle valves, cutlery, steel balls, and various hand tools. Despite their extensive industrial applications, both grades present significant machining challenges due to their poor machinability. During machining, they tend to generate tough and ductile chips with pronounced built-up edges, while their high hardness increases tool wear and complicates tool selection and process planning. Consequently, determining optimal cutting parameters and an appropriate machining environment is crucial for improving the machinability of martensitic stainless steels and overcoming these challenges.

Different studies have been done on machining optimization and improvement in surface quality on hard and stainless steels using various methods and optimizations. Supriya & Choudhury [1] have applied Taguchi method to achieve optimal surface roughness and tool wear prediction during hard turning. Their investigation on AISI 4340 steel revealed that multilayer TiN coated tools performed better than uncoated tools particularly at high speed and low feed. Patel et al. [2] made a comparative study between ultrasonic assisted turning (UAT) and conventional turning on MSS 420. UAT process was found to decrease the surface roughness by 43% and power consumption by 3.13%. In a similar way, Selvaraj et al. [3] studied dry milling of Duplex steels and observed that increased spindle speed decreases the cutting forces and surface roughness while increased feed rate increased cutting forces. Kekang et al. [4] produced laser clad TiC reinforced 420 MSS coatings and found that addition of TiC refined microstructure, increased hardness and wear resistance of the alloy. In case of 6wt% TiC, the highest hardness value was obtained while in case of 4 wt% TiC, the wear volume was reduced to 25% of that of unreinforced 420 MSS. Alper et al. [5] observed that Vegetable-based MQL cooling/lubrication system with 1% nano-molybdenum disulfide had resulted in reduction in tool wear and surface quality improvement in the case of MSS 420.

Philip et al. [6] employed Response Surface Methodology (RSM) to optimize the milling process of Duplex Stainless Steel and discovered that higher spindle speeds, lower feed rates and lower axial depth of cuts result in the best surface finish. Rajeev et al. [7] emphasized the use of Dry machining as environmentally friendly option compared to the traditional machining processes along with tool materials and coatings of Ceramic, Diamond and Multilayer coatings to minimize cutting heat and prolonging tool life. Aristumuno et al. [8] developed a model for estimation of cutting forces while machining the martensitic alloy with the aid of specific insert shapes at low feed rates and validated it experimentally for Jethete-M152 steel with good match between calculated and experimental results. Sai and Bouzid [9] have optimized face milling process for Duplex Stainless Steel and found that both very low and very high cutting speed negatively impacted on surface quality due to BUE formation and vibration of the tools. Process optimization, tool wear, and grey relational analysis have been recommended by Gyanesh and Rabindra [10] as essential factors for enhancing the machining performance, efficiency of cutting operations, and surface integrity of hardened steels. Additive manufacturing of stainless steels has been reviewed by Mahdieh et al. [11], where they pointed out that additive manufacturing of stainless steels has the capability to manufacture customized complex components along with the effect of process parameters on the structural and mechanical characteristics as well as corrosion resistance of stainless steels.

In the recent developments, there has been considerable attention from the researchers in relation to the optimisation of the MSS grades during the machining operations. Although many reports can be found for the turning process of MSS, there are very few reports available for the milling operations, specifically CNC dry milling which has been selected for the research .Further studies and analysis need to be performed in optimising the cutting parameters during the milling of MSS grades specifically MSS

410 and MSS 420.MSS 410 and MSS 420 have a broad spectrum of applications; however, there is a problem related to low machinability. Stiff, draggy chips along with heavy build-up edges are formed due to hard metal. Selection of tool, processing, etc. is very critical. Selection of appropriate cutting parameters especially for maintaining temperature is needed for machining of Martensitic Steel. The decision has been made in order to perform dry machining taking into consideration the environmental impact and health risks associated with the cutting fluid

2. METHODOLOGY

The enhancement of machining efficiency and output quality strongly depends on proper selection of process variables. In this work, parameter optimization for CNC dry milling of AISI 410 and AISI 420 martensitic stainless steels was carried out using the Taguchi approach. The influence of rotational speed, tool feed, and cutting depth on thermal response was investigated. In order to eliminate the environmental and occupational issues associated with cutting fluids, all trials were conducted in a dry cutting environment without any coolant or lubricant application.

2.1 Selection of Work and Tool Material

Martensitic stainless-steel grades AISI 410 and AISI 420 were used as the workpiece materials. The specimens were supplied in plate form, measuring 100 mm × 80 mm × 50 mm. CNC milling was carried out using a BMV 40 T20 machining center. A Tagutec milling cutter (TE90AP 216-16-09-L) with a diameter of 20 mm, fitted with TiCN-coated tungsten carbide inserts (APKT 09T308R-EM), was used for all experiments. Cutting temperature during milling was measured with an Amprobe IR-750 infrared thermometer. The experimental plan was developed using a Taguchi L9 orthogonal array (OA), as shown in Figure 1. The chemical compositions and mechanical properties of the selected workpiece materials are provided in Table 1 and Table 2.

Fig.1.Experimental setup (Karunya institute of Technology and Science, CNC LAB)

Table 1. Chemical composition of 410 and 420 MSS grade [12]

Alloy	Cr	Ni	C	Mn	Si	Mo	P	S	Cu	Fe
AISI 410	11.94	0.519	0.131	0.816	0.36	0.24	0.024	0.025	0.077	Balance
AISI 420	12.34	0.271	0.201	0.741	0.56	0.21	0.027	0.006	0.108	Balance

Table 2. Annealed mechanical properties of SS 410 and SS 420 MSS [13].

Alloy	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation %	Hardness (HRC)
AISI 410	510	290	34	38-45
AISI 420	586	310	29	53-57

The CNC dry milling tests were conducted by using BFW make BMV 40 T20 vertical machining center. The spindle motor of this machine is 10 kW and operates between 60 to 6000 rpm of spindle speed. TE90AP 216-16-09-L. The CNC dry milling tests were conducted in Karunya Institute of Technology and Sciences, Coimbatore.

2.2. Cutting parameter selection

The study considered spindle speeds between 1000 and 2000 rpm and depths of cut from 0.3 to 0.9 mm, while keeping the feed rate constant at 60 mm/min. Three levels were assigned to each parameter for the experiments. The selected cutting parameters and their levels are listed in Table 3.

3. RESULTS

The experiments were carried out using a Taguchi L9 orthogonal array, with the results presented in Table 3. Minitab 19 software was used to analyze the data and identify the optimal cutting parameters. The signal-to-noise (S/N) ratio was used to evaluate the deviation from the desired response, while ANOVA was applied to assess the effects of spindle speed and depth of cut on cutting temperature. A constant spindle speed of 60 mm/min were considered in this experiment.

Table 3. Experimental results of L_9 experiment

Exp. No.	Spindle Speed N (rpm)	Depth of Cut (mm)	Temperature - MSS 410 (°C)	Temperature - MSS 420 (°C)
1	1000	0.3	48.4	53.4
2	1000	0.6	49.1	54.1
3	1000	0.9	52.08	57.1
4	1500	0.3	50.2	55.1
5	1500	0.6	51.2	56.2
6	1500	0.9	53.6	58.6
7	2000	0.3	55.8	60.8
8	2000	0.6	56.4	61.4
9	2000	0.9	65.2	70.2

3.1. Signal to Noise Ratio Analysis

Table 4 and Table 5 present the response tables for the S/N ratios of temperature for both grades. The results show that the highest S/N ratios for MSS 410 and MSS 420 are achieved at the lower levels of spindle speed and depth of cut.

Table 4. Response table for S/N ratios of temperature - MSS 410

Level	Cutting Speed	Depth of Cut
1	-33.74	-33.15
2	-34.20	-34.54
3	-35.42	-35.67
Delta	1.69	2.52
Rank	2	1

Table 5. Response table for S/N ratios of temperature - MSS 420

Level	Cutting Speed	Depth of Cut
1	-34.64	-34.02
2	-34.97	-35.32
3	-36.05	-36.31
Delta	1.42	2.29
Rank	2	1

Figure 2 and Fig. 3 (Generated using Minitab 19 statistical software) present the S/N ratio main effects plots for the cutting temperature of MSS 410 and MSS 420, respectively. Figs. 2 and 3 represents temperature values main effects plot for S/N ratios. From Figs 2 and 3, larger values of ratios of S/N for temperature of grades (MSS) 410 and 420 are obtained at spindle speed (1000rpm) and Depth of cut (0.3mm) at levels.

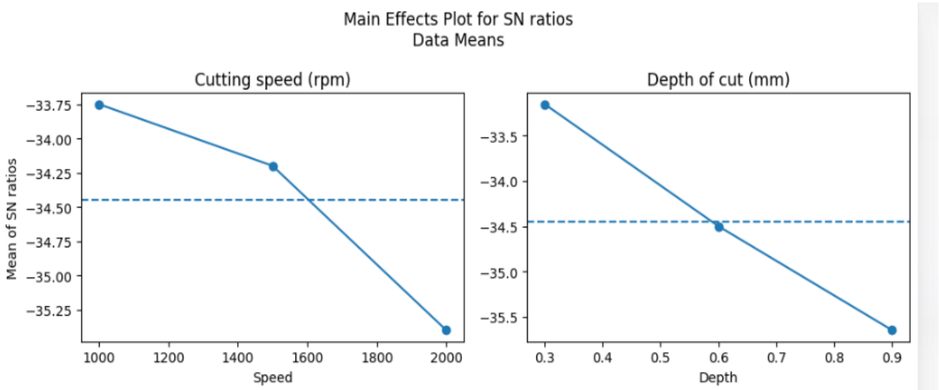

Fig 2. Main effects plot for S/N ratios of temperature - MSS 410

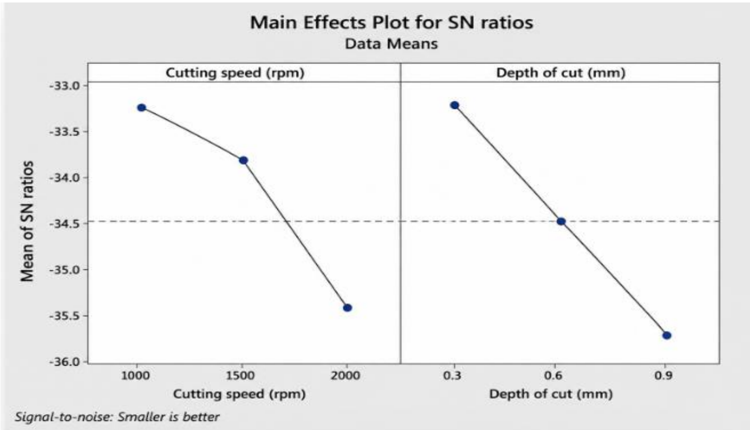

Fig. 3. Main effects plot for S/N ratios of temperature - MSS 420

3.2. Analysis of Variance (ANOVA)

Table 6 and Table 7 show that depth of cut has higher impact on cutting temperature, followed by spindle speed. For AISI 410, the contributions of spindle speed and depth of cut are 27.60% and 62.84%, respectively. For AISI 420, the corresponding contributions are 23.43% and 67.14%. These findings confirm that depth of cut is the dominant factor affecting cutting temperature in both martensitic stainless-steel grades.

Table 6. ANOVA for temperature - MSS 410

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	Contribution (%)
Spindle Speed (rpm)	2	0.000061	0.000061	0.000031	130.48	27.60
Depth of Cut (mm)	2	0.000139	0.000139	0.000070	297.05	62.84
Error	20	0.000005	0.000005	0.000004	-	2.12
Total	26	0.000221	-	-	-	100.00

Table 7. ANOVA for temperature - MSS 420

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	Contribution (%)
Spindle Speed (rpm)	2	0.000055	0.000055	0.000027	100.46	23.43
Depth of Cut (mm)	2	0.000157	0.000157	0.000080	287.93	67.14
Error	20	0.000006	0.000006	0.000003	-	2.33
Total	26	0.000235	-	-	-	100.00

4 DISCUSSION

4.1 Impact of work piece material on Temperature

According to Table 3, it is seen that the temperature value of MSS grade 420 is higher than the value of MSS grade 410. The basic cause of such an observation lies in the chemical composition of both types. There exists a significant difference in the composition of C and Cr. The composition of C and Cr in MSS grade 420 is 0.201% and 12.34%, while in MSS grade 410 it is 0.13% and 11.94%. Metal carbides get formed as the result of increase in the percentage of Chromium and hence increasing the properties of toughness, hardness, strength and corrosion resistance. It is known that the higher percentage of carbon distorts the crystal lattice structure. Distortion of the crystal lattice structure leads to the work hardening of the metal. Vacancies or voids present in the metal got filled with the help of carbon and prevented the motion of the atoms on the crystal site. Thus, strength and hardness get increased whereas the properties of ductility, forgeability and machinability get decreased.

4.2 Comparison of Optimum values for MSS 410 and MSS 420

For cutting temperature, the optimum parameters were a rotational speed of 1000 rpm and a cutting depth of 0.3 mm, with a constant feed of 60 mm/min. The corresponding experimental optimum temperatures for both MSS grades are presented in Table 8.

Table 8. Optimized values of cutting parameters for temperature

Spindle Speed, N (rpm)	Feed Rate, f (mm/min)	Depth of Cut, d (mm)	Temperature - MSS 410 (°C)	Temperature - MSS 420 (°C)
1000	60	0.3	48.4	53.4

Across all experimental trials (Table 3), MSS 420 consistently exhibited higher cutting temperatures than MSS 410, mainly due to its higher carbon and chromium content.

5. CONCLUSION

Using the Taguchi approach, the cutting parameters, spindle speed and depth of cut were optimized for MSS grades 410 and 420 during CNC dry milling. Based on the analysis, the following conclusions can be drawn:

1. The optimum cutting parameters for minimum cutting temperature of the tool for MSS grades 410 and 420 are a spindle speed of 1000 rpm and a depth of cut of 0.3 mm.
2. ANOVA results show that the cutting temperature is influenced primarily by the depth of cut, followed by the spindle speed.
3. Spindle speed and depth of cut contribute approximately 28% and 63% respectively to the cutting temperature of MSS 410, and approximately 23% and 67% respectively to that of MSS 420.
4. MSS grade 420 exhibits higher cutting temperature values than MSS grade 410, owing to the difference in chemical composition and the higher carbon and chromium content present in MSS 420.

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