Analysis and Optimization of Surface Roughness while Machining SS304 using Green Lubricant

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Abstract

Stainless steels (SS) are used in a variety of precision, scientific, and industrial applications. All demand excellent surface properties for better functional performance of the products made by SS. Analysis, modeling, and optimization of machining of SS can result in process parameter combinations which facilitate to obtain better surface properties while machining SS using conventional processes. This paper reports the investigation on surface roughness (mean roughness depth) of SS304 machined by conventional turning using TiAlN/TiN coated tools under the influence of green lubricant. In this work total nine experiments with two replicates each have been conducted by varying three important machining parameters i.e. cutting speed, depth of cut, and feed rate at three levels each. A detailed effect of process parameters on mean roughness depth is discussed. Analysis of variance study is also reported. Process parameter optimization resulted in the optimum value 4.81 µm of mean roughness depth.

Keywords
Lubrication, Machinability, Machining, Roughness, Steel

1. Introduction

Stainless steel (SS) is one of the most extensively used engineering materials. It has many applications such as in bio-medical instruments, tanks and vessels, automobile and machine components, scientific devices etc (Davison et al, 1986; Prasad and Rao, 2013). But it is a difficult-to-machine (DTM) material and possesses poor machinability at ordinary machining conditions. SS304 is one of the important types of stainless steel. Tool wear, work surface deterioration, high machining cost, and environmental footprints are some of the challenges occur while machine this material by conventional processes (Sharma and Gupta, 2019). Process parameter optimization, using green lubricants and lubrication techniques, employing assisted machining; and using treated and coated tools are some of the ways to overcome the machining challenges for any DTM material such as SS (Gupta and Laubscher, 2017). There have been some past attempts to investigate and analyze the machinability of stainless steels, which are discussed here as under.

Paro et al. (2001) reported that stainless steel is always assumed as DTM material due to high degree of hardening and low thermal conductivity. Therefore, the selection of tool material is made considering its reliability and durability. A number of researchers worked on the machining of austenitic stainless steel. Abou-El-Hossein and Yahya (2005) machined stainless steel and investigated the different failure modes of the cutting tool. Ciftci (2006) studied the effect of machining variables during turning of SS by CVD coated tool without any cutting fluid. Dry machining was found as the sustainable alternate of wet turning. Shao et al. (2007) studied the tool wear mechanism in the milling process and observed that the different types of wear mechanisms namely abrasion, adhesion, and attrition were found at different stages. Machining of stainless steel in three different environment namely wet, dry and cryogenic cooling was done by Manimaran and Kumar (2013). Cryogenic cooling was identified a green lubrication technique that resulted in the improved machinability of SS. In a recent study, Sharma and Gupta (2019) machined SS304 material and investigated the influence of coated and uncoated tool on the tool wear. It was found that tool wear is a combination of abrasion, adhesion and cutting-edge failure at different combinations of process parameters. It was also recommended that the dry cutting under coated tools has potential and can be explored further to establish as an alternate to the conventional wet cooling based machining.

It is evident from the available literature that dry machining, cryogenic cooling, and coated tools can significantly enhance the machinability of stainless steel type DTM material. But the gap exists in terms of exploring alternate lubricants such as green lubricants and machining of SS under their influence with various tool materials and coatings. Moreover, mean roughness depth which is the most prominent roughness parameter and depicts the actual condition of the machined surface hasn't been explored much. This work fulfils the gap where SS304 has been machined using TiAlN/TiN multi-layer coated carbide tool inserts under green lubrication and a detailed analysis of the machinability has been done. The scope of this paper is limited to the study on analysis and optimization of mean roughness depth.

2. Materials and Methods

In the present work, stainless steel grade 304 has been machined on Colchester Mascot 1600 semi-automatic heavy-duty lathe. The multi-layer TiAlN/TiN alternate layer coated carbide tool inserts were used under the influence of green lubricant/cutting fluid at wet cooling conditions. The characteristics of biodegradable synthetic cutting fluid of BECHEM make Hydrostar HEP 68 with synthetic esters are- kinematic viscosity: 39.11 mm2/s at 40°C; density: 0.9199 g/cm3 at 20°C; flash point: > 290°C and pour point: 8°C. The sequence of operations performed in the present work is shown in Figure 1. Tmteck (TMR200) make roughness tester has been used for the measurement of mean roughness depth R_z. Three important machining parameters are cutting speed (CS), feed rate (FR) and depth of cut (DC). The process parameters, their levels, units and notation are given in Table 1.

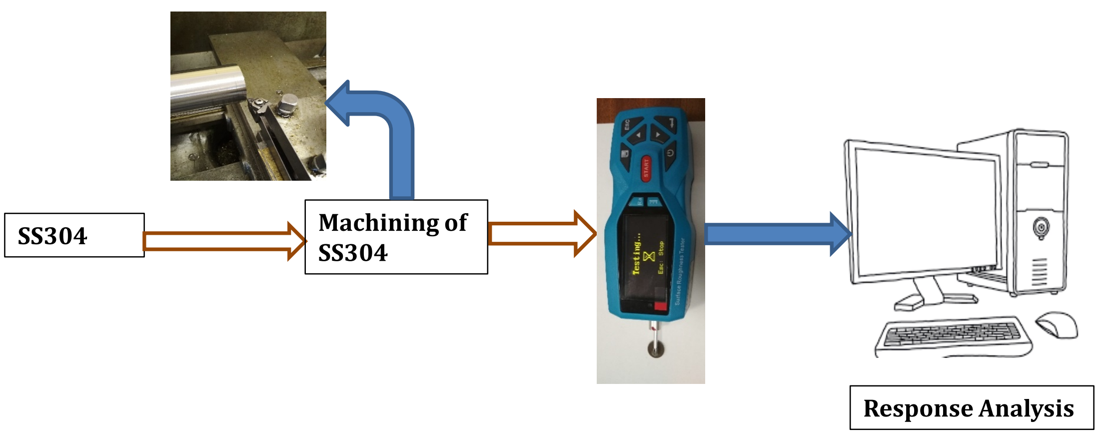


Fig. 1 Sequence of steps performed during machining of SS304

Table 1 Details of machining parameters

Parameter		**Levels**	
	L_1	**L_2**	**L_3**
Cutting speed (m/min)	70	120	170
Feed (mm/rev)	0.1	0.15	0.2
Depth of cut (mm)	0.5	1	1.5
	Cutting speed (m/min)	**Feed (mm/rev)**	**Depth of cut (mm)**
1	70	0.1	0.5
2	70	0.15	1
3	70	0.2	1.5
4	120	0.1	1
5	120	0.15	1.5
6	120	0.2	0.5
7	170	0.1	1.5
8	170	0.15	0.5
9	170	0.2	1

The process parameter combinations based on Taguchi L_9 orthogonal array are also shown in Table 1. To minimize the level of experimental error two replications for each experiment has been done. Moreover, the average of three roughness measurements has been considered.

3. Results and Discussion

3.1 Statistical Analysis

Table 2 and 3 present the results of ANOVA for R_z with the help of which statistical significance of machining parameters has been done. The P-value <0.05 proves the significance of all three machining parameters. Subsequently, the percentage contribution for CS, F and DoC are 30.26%, 33.21% and 36.38% respectively. Table 4 gives the ANOVA of R_z for S/N ratio and it is clear that the percentage contribution of each process parameter follow the same pattern as followed in case of raw data.

Table 2. ANOVA for R_z raw data

Source	DF	SS	PC	MS	F	P
Cutting Speed	2	3.6681	30.26	1.83404	208.17	0.005
Feed	2	4.0260	33.21	2.01301	228.49	0.004
Depth of cut	2	4.4100	36.38	2.20498	250.28	0.004
Residual Error	2	0.0176	0.15	0.00881		
Total	8	12.1217				
DF- degree of freedom, SS- sum of squares, PC- percentage contribution MS- mean sum of squares, F- F-ratio, P- P value						

Table 3. ANOVA for R_z S/N ratio

Source	DF	SS	PC	MS	F	P
Cutting Speed	2	5.4363	30.75	2.71815	51.90	0.019
Feed	2	5.6892	32.19	2.84458	54.32	0.018
Depth of cut	2	6.4461	36.47	3.22306	61.55	0.016
Residual Error	2	0.1047	0.59	0.05237		
Total	8	17.6763				

3.2 Effect of Process parameters on R_z

Figure 2 depicts the trends of variation of R_z with three machining parameters. It is observed that the minimum R_z is obtained at high CS (170m/min), low F (0.1mm/rev) and low DoC (0.5mm). At high CS, a low value of R_z has been observed, the reason being the reduction in built-up edge (BUE) formation at high speed generated better surface finish (Grzesik, 2017; Sharma and Gupta, 2019). On the other hand, lower values of feed rate and depth of cut minimize the cutting forces and vibrations during machining which consequently results in surface finish improvement. At high value of DoC, BUE formation increases, which consequently increases the possibilities of sticking of chips to the tool and further degrade the cutting edge of tool. At this stage, the machining produces a rough surface certainly with high value of R_z.

Fig. 3 depicts the counter plots between different input parameters and the R_z. Figure 3a represents the variation of CS and F with R_z by the color codes. It is seen that low value of F and high value of CS provide minimum Rz. Similarly, Fig. 4b and 4c suggest the machining to be conducted at low values of DOC and F to obtain minimum Rz.

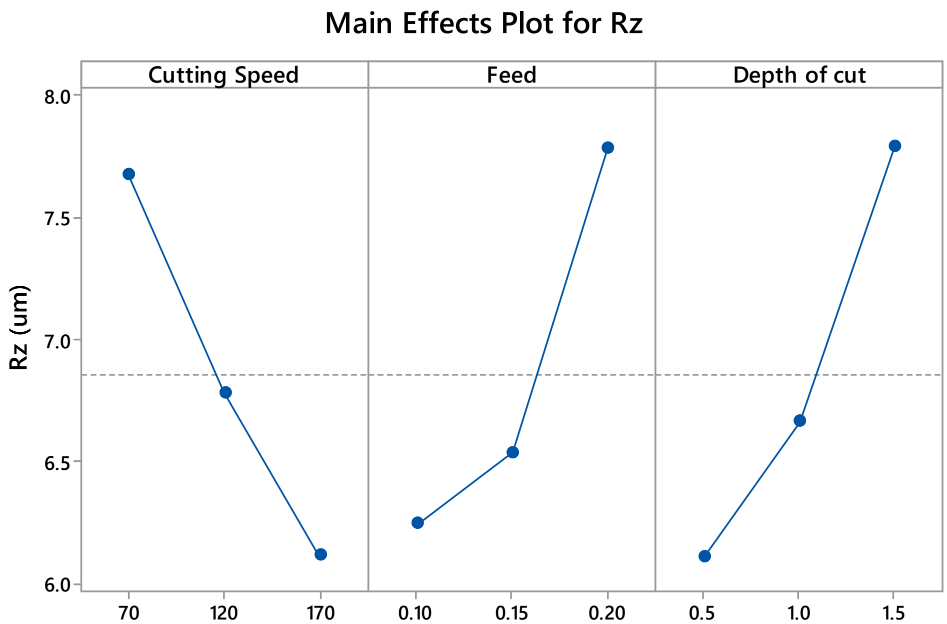
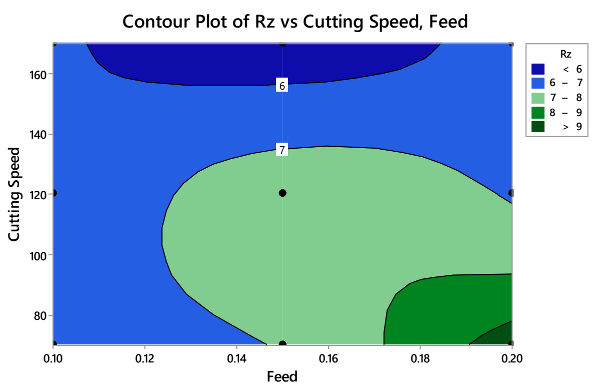
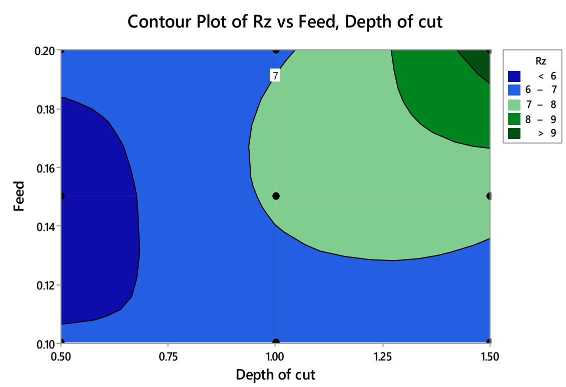


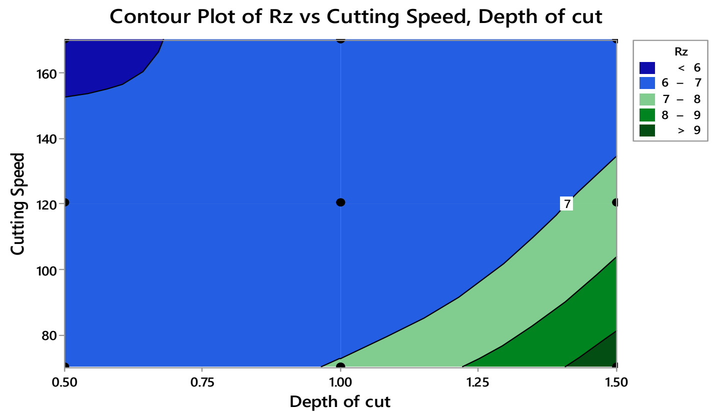
Fig. 2 Graphs of variation of R_z with machining parameters



(a)



(b)



(c)

Fig. 3 Counter plots showing combined effects of (a) CS and F, (b) F and DoC, (c) CS and DoC, on R_z

3.3 Optimization

Tables 4 and 5 are the response tables of raw data and S/N ratio. Both suggest the same parameter settings for optimum response i.e. R_z. It is evident that minimum Rz corresponds to the third level of CS, first level of F and DoC. Therefore, mean value of R_z can be identified using Equation 1 below.

$$\mu_{Rz} = (CS)_3 + (F)_1 + (DoC)_1 - 2\,(T) \quad (1)$$

where, T- mean of the all experimental values.
All other values of CS, F and DoC can be found from Table 4.
$\mu_{Rz} = 4.75\mu m$

Table 4. Response Table for Raw data

Level	Cutting Speed	Feed	Depth of cut
1	7.673	**6.245**	**6.113**
2	6.785	6.540	6.665
3	**6.115**	7.788	7.795
Delta	1.559	1.543	1.682
Rank	2	3	1

Table 5. Response Table for S/N ratio

Level	Cutting Speed	Feed	Depth of cut
1	-17.56	-15.91	-15.66
2	-16.60	-16.19	-16.45
3	-15.66	-17.72	-17.71
Delta	1.90	1.81	2.06
Rank	2	3	1

The validation experiment has been performed at the suggested optimal setting for R_z. Table 6 shows the optimal parameter setting and the values of R_z predicted at optimal setting along with its value obtained after confirmation experiment. The optimal parametric setting suggested by ANOVA is CS: 70m/min; F: 0.1mm/rev;

DoC: 0.5mm. The optimum value of R_z obtained after confirmation experiment is 4.81 μm, which is much better than the values corresponding to the nine experimental runs and very close to the predicted value.

Table 6. Results of optimization

Response Variable	Parametric Setting by ANOVA	Predicted (μm)	Experimental (μm)
R_z	$(CS)_3(F)_1(DoC)_1$	4.75	4.81

4. Conclusions

In this paper, an investigation on analysis and optimization of surface roughness during turning of SS304 by coated tools and under the influence of green cutting fluid is reported. Effects of machining parameters on mean roughness depth, results of ANOVA study, and optimization of machining parameters for surface finish improvement are discussed. The following conclusions can be drawn from this work-

1. Depth of cut was identified as the most significant parameter with a percentage contribution of 36.38% followed by fed rate- 33.21% and cutting speed- 30.26%.
2. Analysis of the results presented that optimum parameter combination i.e. cutting speed-170m/min, feed rate- 0.1mm/rev and depth of cut- 0.5mm corresponds minimum R_z.
3. Confirmation experiment conducted at optimal parameter setting resulted in optimum value of Rz- 4.81 μm.

In essence, it can be concluded that machinability challenges of SS304 type difficult-to-machine materials can be overcame by sustainable techniques where green cutting fluids possess the capability to prevent excessive tool wear and generate good surface quality along with keeping the environment clean and green.

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References

Davison RM, Laurin TR Redmond JD, Watanabe H and Semchyshen M 1986 A review of worldwide developments in stainless steels. Mater. Des. 7 111.

Prasad S N, and Rao M N 2013 Stainless steel – a versatile engineering material for critical applications Adv. Mater. Res. 794 44.

Kapil Gupta and RF Laubscher (2017), "Sustainable Machining of Titanium Alloys- A Critical Review", Proc. IMechE, Part B: Journal of Engineering Manufacture (Sage), 231 (14), 2543-2560

Paro, J., Hanninen, H., and Kauppinen, V., Tool wear and machinability of HIPed P/M and conventional cast duplex stainless steels, *Wear* vol. 249, pp. 279–284, 2001.

Abou-El-Hossein, K.A., and Yahya, Z., High-speed end-milling of AISI 304 stainless steels using new geometrically developed carbide inserts, *Journal of Materials Processing Technology*, vol. 162/163, pp. 596–602, 2005.

Ciftci, I., Machining of austenitic stainless steels using CVD multi-layer coated cemented carbide tools, *Tribology International*, vol. 39, pp. 565–569, 2006.

Shao, H., Liu, L., and Qu, H.L., Machinability study on 3% Co–12% Cr stainless steel in milling, *Wear*, vol. 263, pp. 736–744, 2007.

Manimaran, G., and Kumar, M.P., Effect of cryogenic cooling and sol–gel alumina wheel on grinding performance of AISI 316 stainless steel, *Archives of Civil and Mechanical Engineering*, vol. 13, pp. 304–312, 2013.

Sharma, N., and Gupta, K., Influence of coated and uncoated carbide tools on tool wear and surface quality during dry machining of stainless steel 304, Material research Express, vol. 6, 086585, pp. 1-18, 2019.

Krolczyk, G., Legutko, S., and Gajek, M., Predicting the surface roughness in the dry machining of duplex stainless steel (DSS), *Metalurgija*, vol. 52, pp. 259–262, 2013.

Grzesik, W., Advanced Machining Processes of Metallic Materials: Theory, Modelling and Applications, 2nd Edition, Elsevier, Amsterdam, Netherland, 2017.

Biographies

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