STUDY OF THE SURFACE FINISH WHEN TURNING HARDENED STEELS

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Abstract

This study concentrates on the optimization of process parameters for surface roughness when turning hardened bearing steels using coated ceramic cutting tools and developed the multiple regression models for the surface roughness based on the factors cutting speed, feed rate, depth of cut and cutting fluid. The experimental results indicated that the feed rate was found to be a dominant factor on the surface roughness of Ra and Rz, but the other factors did not indicate the significant effect. In addition, optimal testing parameter for the surface roughness was determined. Average surface roughness obtained was about 0.79 and 4.102 μm for Ra and Rz, respectively, when machining the hardened steels. Furthermore, ANOVA revealed that the feed rate exerted a largest effect on the surface finish at contribution of 64.03%, followed by the depth of cut at 10.47%, respectively.

Key words: *Bearing steel, cutting tool, surface finish, feed rate, depth of cut, lubrication, factorial design*

1. INTRODUCTION

Hardened steels are used in some areas such as food industry, automotive and aerospace industry for making components such as bearings, gears, shafts, and cams, but it is difficult to machine it. These steels are either machined by grinding process or using ceramics/cubic boron nitride (CBN) tools, but grinding operations are time consuming. Due to having unique mechanical, physical properties like high hardness, wear resistance and chemical resistance, these are found many applications (Rangaro et al. 2011). **S**urface roughness is one of the most important requirements in the manufacturing process because it improves its quality significantly by increasing the fatigue strength, corrosion resistance, or creep life. Various studies were conducted to investigate the performance of CBN and ceramic tools when machining hard steels or hardened steels (Bouach et al. 2011; Aouici et al. 2011;Suresh et al. 2012; Chavoshi and Tajdari 2010). Sahin (2009) described a comparison of tool life between ceramics and cubic boron nitride (CBN) cutting tools when machining hardened bearing steels using the Taguchi method. The results indicated that the *V* was found to be a dominant factor on the tool life, followed by the TH, lastly the *f*. Lim et al. (2001) showed that the TiC coating was more effective when machining carbon 1045 grade, decreasing tool wear rates by half an order magnitude. Khrais and Lin (2006) reported the dry cutting was better than wet cutting at round 200–400m/min speed for machining of AISI 4140 steels with coated inserts. However, Che Haron et al. (2001) reported that wet cutting was better than dry cutting for coated carbide tools when machining tool steels (23 HRC).

Avila and Abrao (2001) observed that the application of a cutting fluid based on an emulsion without mineral oil resulted in longer tool life compared to dry cutting of AISI 4340 steel. The surface roughness increased with the increase of feed rate and almost decreased with the increase of workpiece hardness (Azizi et al.2016). The results revealed that the feed rate, workpiece hardness and cutting speed had significant effects for the surface roughness. The wear resistance of CBN composites was found to be superior than that of the ceramic tools when machining of AISI 4340 steel (Barry and Byrne 2001), 100Cr6 bearing steel (Benga and Abrao 2003) and 52100 bearing steels (Huang and Dawson 2005, Poulachon et al. 2001, Polulachan et al.2004 &Kumar et al. 2003).

Several researches have been studied the hard turning of bearing or hardened steels (EN24) using different types of ceramics or CBN tools in terms of surface finish (Kumar et al. 2006, Fnides, Yallese, Mabrouki, and Rigal 2011, Feng et al.2002, Grzesik et al.2006). Davim (2001) indicated that

the cutting velocity had a greater effect on the roughness, followed by the feed rate. Later work by Davim and Figueira (2006) concluded that the tool wear was highly influenced by the cutting velocity. Sahin and Motorcu (2008a) reported that CBN cutting tools produced a better surface roughness than those of KY1615 cutting tools in all experimental conditions. The latest work by Sahin and Motorcu (2008b) indicated that the cutting speed exerted the greatest effect, followed by hardness of the tool. Lima et al. (2005) reported that the surface roughness of AISI D2 steel with mixed alumina inserts allowed a surface finish as good as with cylindrical grinding. Adesta et al. (2009) showed that increase in negative rake angles caused higher wear and poor surface finish. Gaitonde et al.(2009a) indicated that CC650WG wiper insert performed better with reference to surface roughness and tool wear. The surface roughness was minimal at lower values of depth of cut and machining time in case of CC650 and CC650WG inserts machining AISI D2 cold work tool steel. Fnides et al.(2009) revealed that the effect of feed rate on the surface roughness was more significant than the cutting speed for hardened steel. Elmunafi (2012) found that the effects of cutting speed and feed rate on the surface roughness were statistically significant. The wiper inserts were able to produce better surface finish for coated ceramics.

The objectives of this work were to investigate the effect of cutting speed, feed rate, depth of cut and cutting fluid parameters to optimize surface roughness under conditions using Taguchi's robust design methodology. Furthermore, the prediction models for surface roughness were developed the in turning the hardened steels using multiple regression analysis.

2. EXPERIMENTAL

2.1. Materials

The machine used for turning tests was a Johnford TC35 Industrial type of CNC lathe machine. The type of cutting tool was ceramic cutting tool for the present work. Coating substance takes place on the mixed ceramic substrate and PVD-TiN coated mixed ceramic with a matrix of Al2O3 (70%):TiC (30%) +TiN, which is called as KY4400 grade. The insert type was TNGA 160408-KY4400. The insert was rigidly attached to a tool holder of ISO designation of PTBNR 2525-16. These ceramic-based tools are commercially available inserts according to ISO code, supplied by Kennametal Inc. for the turning tests. The material used throughout this work was an AISI 100Cr6 steel, which was the bearing steel containing C (0.99%), Mn (0.39%), Si (0.16%), Cr (1.40%), Ni (1.4%) and balance Fe. Its hardness was about 64 HRC. Samples to be cut were in the cylindrical form of steel bars with diameter of 98mm, length of 220 mm. These bars were machined under dry condition. The work material bars were trued, centered and cleaned by removing a 1mm depth of cut from the outside surface, prior to the actual machining tests. After each test, the surface finish was measured with the marl type of style surface measurement.

2.2. Experimental design

An orthogonal array and ANOVA were applied to investigate the influence of process parameters on the surface finish of 100Cr6 bearing steels. The factorial design of experiment approach eliminates the need for repeated experiments and thus saves time, material, and cost. This approach identifies not only the significant control factors, but also their interactions influencing the wear rate predominantly.

This experiment specifies four principle wear testing conditions including the cutting speed (A), feed rate (B), depth of cut (C), and cutting fluid (D) of the tested materials as the process parameters. Codes and levels of control parameters were shown in Table 1. This table showed that the experimental plan had two levels.

Table 1. Control parameters and their levels

Symbol	Main control parameters	Level 1	Level 2
A	Cutting speed (m/min)	60 (-1)	120 (1)
B	Feed rate (mm/rev.)	0.12 (-1)	0.24 (1)
C	Depth of cut (mm)	0.2 (-1)	0.6 (1)
D	Cutting fluid(enviro.)	Dry (-1)	Bor oil (1)

A standard Taguchi experimental plan with notation L16 (2^4) was chosen, as shown in Table 2. Each combination of experiments was repeated twice to acquire a more accurate result in the process. The objective of ANOVA was to evaluate the significance of testing parameters and their interactions on the surface finish of steels. The final step in design of experiment approach was to predict and verify the arrived values for the optimal combination level of control factors.

Table 2. Experimental lay out, results for the surface finish of machining AISI 100Cr6 bearing steel.

	Control parameters				Ra measurements			Rz measurements			Avg. output	
Exp. run	Cutting speed (A)	Feed rate (B)	Depth of cut (C)	Enviro. (D)	Ra1	Ra2	Ra3	Rz1	Rz2	Rz3	Avg. Ra (µm)	Avg. Rz (µm)
1	60	0.12	0.2	Dry	0.549	0.474	0.477	2.88	2.77	2.52	0.495	2.7233
2	120	0.12	0.2	dry	0.431	0.418	0.427	2.21	2.15	2.2	0.4253	2.1866
3	60	24	0.2	dry	1.023	0.997	0.928	5.19	4.77	5.07	0.9826	5.010
4	120	24	0.2	dry	1.121	1.088	0.991	5.6	5.22	4.83	1.0666	5.2166
5	60	0.12	0.6	dry	0.416	0.404	0.411	2.18	2.02	2.48	0.4103	2.2266
6	120	0.12	0.6	dry	0.483	0.451	0.452	2.62	2.28	2.43	0.447	2.4433
7	60	0.24	0.6	dry	1.18	1.18	1.25	5.32	5.16	5.52	1.2033	5.3333
8	120	0.24	0.6	dry	1.195	1.462	1.235	5.56	6.85	5.52	1.2973	5.9766
9	60	0.12	0.2	bor oil	0.477	0.436	0.814	5.65	2.49	5.26	0.5756	4.4666
10	120	0.12	0.2	oil	0.377	0.416	0.413	2.07	2.32	7.41	0.402	2.263
11	60	0.24	0.2	oil	0.859	0.848	1.193	4.43	4.64	6.98	0.966	5.350
12	120	0.24	0.2	oil	0.55	0.343	0.334	4.03	2.32	2.16	0.409	2.836
13	60	0.12	0.6	oil	0.74	0.593	0.465	4.37	3.65	2.58	0.5993	3.6333
14	120	0.12	0.6	oil	0.417	0.496	0.472	2.31	2.63	2.5	0.4616	2.480
15	60	0.24	0.6	oil	1.36	1.349	1.416	6.35	6.32	6.5	1.375	6.390
16	120	0.24	0.6	oil	1.515	1.62	1.584	6.89	7.47	7.12	1.573	7.160

3. RESULTS AND DISCUSSION

3.1. Main effect plots

The experimental lay out and results of the surface finish of bearing steels are shown in Table 2 and main effect plots on the surface finish in Fig.1. The tests relevant to this table are carried out at indicated parameters. It was evident from the figure that the surface finish increased with increasing feed rate, depth of cut and but no environment effect was observed while it decreased slightly with increasing the cutting speed of the tested samples (Fig. 1a). Thus, it can be neglected in the variance analysis in the following section. The increases in the surface finish were considerably higher for the feed rate, which was followed by the depth of cut. Furthermore, no variation was observed with changing the environment from dry to cutting fluid condition (Fig.1d).

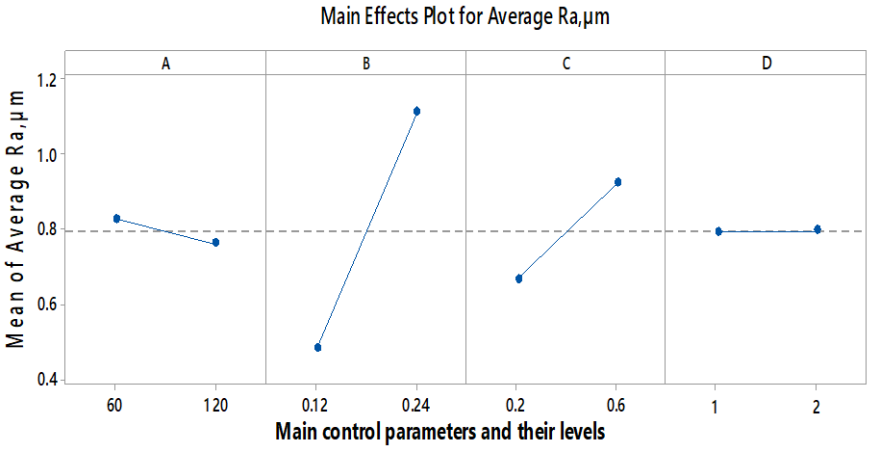


Fig. 1. Main effect plots for the surface roughness in machining hardened steels.

Fig. 2 shows the surface plots of surface roughness of *Ra* versus machining variables (*A,B,C & D*). Figs. 2 (a,b,c and d) indicates the Ra versus cutting speed & feed rate, cutting speed & depth of cut, and cutting speed & cutting fluid, respectively. This configuration verified that the factor of B was dominant effect, but the factors of A, D were not significantly effective. The last figure also exhibited the factor B was found to be effective again, but the factor D was not effective on the weight loss of the tested samples.

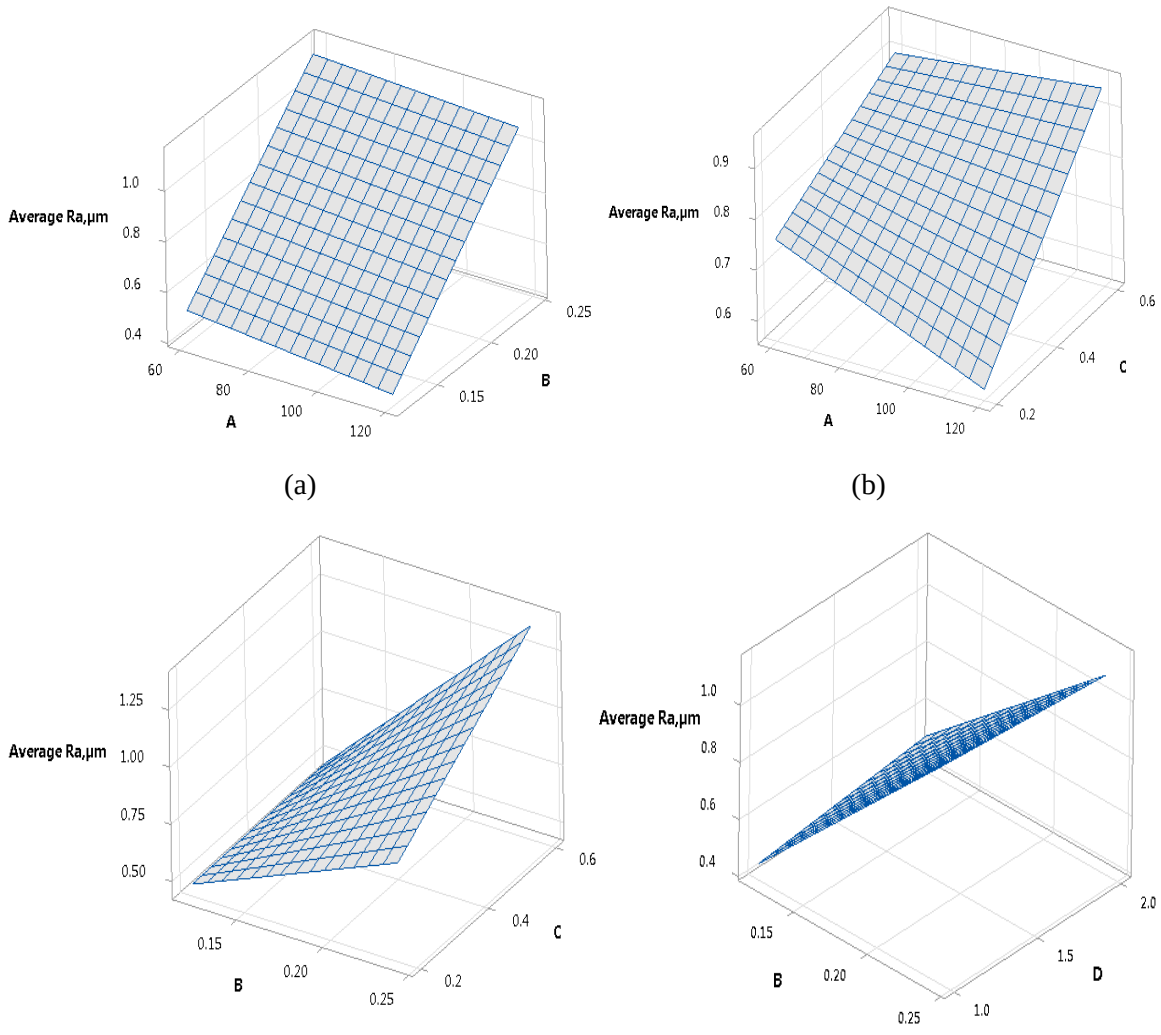


Fig. 2. Surface plots of surface roughness (*Ra*) versus machining variables (*A,B,C&D*). (a) Ra vs. cutting speed (A) &feed rate (B), (b) Ra vs. cutting speed(A) & depth of cut (C), (c) Ra vs. feed rate (B) & depth of cut (C), (d) Ra vs. feed rate (B) & cutting fluid (D).

In a similarly, surface roughness of Rz was measured under the same testing conditions. Fig. 3 shows the surface plots of surface roughness (*Rz*) versus machining variables of cutting speed vs. feed rate (a), Rz vs. feed rate & depth of cut (b), Rz vs. feed rate & cutting fluid, respectively. This figure also confirmed that the dominant effect was shown by the factors of B and C (Fig.3b) while the factors A&D were insignificant effect on the abrasive wear of the epoxy composites (Fig.3a&c). These results are good agreement with the previous study carried out on the hard maching steel (Fnides et al.2009, Elmunafi 2012, Azizi et al.2016).

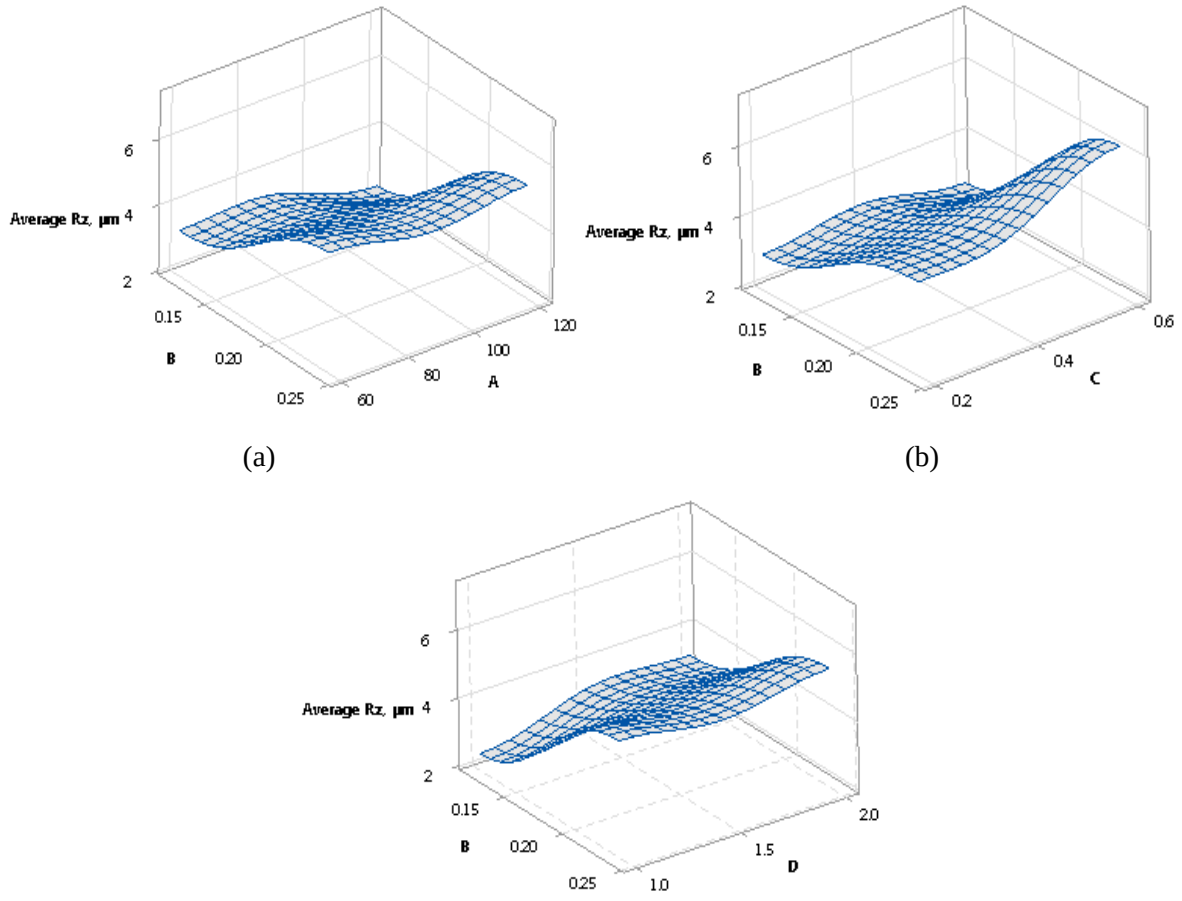


Fig. 3. Surface plots of surface roughness (*Rz*) versus machining variables. (a) Rz vs. cutting speed (A) & feed rate (B), Rz.vs. feed rate (B) vs.depth of cut (C), (b) Rz vs.feed rate (B) &cutting fluid (D).

3.2. Analysis of variance (ANOVA)

The ANOVA results for the surface roughness of hardened bearing steels are listed in Table 3. It is clear from this table that the factor B had statistical and physical significance on the surface finish because test-F value was higher than F5 % column value, followed by the factor C. As it was noted in the last column of ANOVA table, P of each factor on total variations showed degree of influence on the wear results. It could be observed that the factor B (P=64.03 %) had a significant effect, which was followed by the factor C (P=10.47%) on the surface finish of tested samples. The error obtained was about 15.43% due to neglecting the two interaction factors.

Table 3. Analysis of variance for the surface roughness of Ra parameters

Source	DF	Adj SS	Adj MS	F-Value	(P,%)
Model	3	2.1104	0.70347	21.91	-
Linear	2	1.8594	0.92970	28.96	74.50
B	1	1.5981	1.59812	49.78	64.03
C	1	0.2613	0.26129	8.14	10.47
2-Way Inter.	1	0.2510	0.25100	7.82	10.05
B*C	1	0.2510	0.25100	7.82	-
Error	12	0.3852	0.03210		15.43
Total	15	2.4956			

Note: SS is the Sum of Squares, MS is the Mean of Squares, DF is the Degrees of Freedom, P is the Contribution

In a similar way, analysis of variance for the surface roughness of Rz parameter was shown in Table 4. It meant that the B parameter among the others had a significant effect on the surface finish while the parameter C,D were not significant due to its higher values. The error was about 24.58% due to neglecting the two main factors of A&D and their interactions. On the other hand, since total errors were larger than the factor C (4.54%), the factor C was also neglected from both of these results (see Table 3 & 4).

Table 4. Analysis of variance for the surface roughness of Rz parameters.

Source	DF	Adj SS	Adj MS	F-Value	(P,%)
Model	3	32.457	10.8190	12.26	-
Linear	2	29.123	14.5615	16.50	67.66
B	1	27.169	27.1693	30.79	63.11
C	1	1.954	1.9537	2.21	4.54
2-Way Inter.	1	3.334	3.3340	3.78	7.77
B*C	1	3.334	3.3340	3.78	-
Error	12	10.590	0.8825		24.58
Total	15	43.047			

3.3. Correlations

The correlations between the main factors cutting speed (A), feed rate (B), depth of cut (C) and cutting fluid (D) and the surface roughness of the samples were obtained by multiple regressions. The obtained correlations were as follows. The first order model equation for the surface roughness prediction is given the following.

Regression equation in uncoded units for Ra;

*Average Ra, μm = 0.341 + 1.09 B - 1.240 C + 10.44 B*C* (1)

where *Ra* mean is the mean surface roughness Eq. (1) indicated that the feed rate increased the surface finish, but the depth of cut decreased the machined surface sample when machining the hardened steel. The model had an adjusted R^2 value of 84.6%.

Regression equation in uncoded units for Rz;

*Average Rz, μm = 2.24 + 6.50 B - 5.10 C + 38.0 B*C* (2)

Where mean *Rz* is the mean surface roughness Eq. (2) indicated that the feed rate exhibited the significant effect on the surface finish. An adjusted R^2 value of 75.4% showed that 75.4% of the variability in the surface roughness mean was explained by the model with factors of B and C. The lower value of R^2 might be resulted from the contribution of the parameter C.

3.4. Confirmation test

The final step was to verify the improvement of the quality characteristic using the optimal levels of design parameters. According to the prediction of Eq.(1), its Ra is about 0.452 μm, which was the higher value within the obtained experimental result of 0.42 (Table 5). This table indicates a comparison of the predicted surface finish with the actual surface finish using the optimal testing parameters. It can be seen that the difference between verification and calculation was in the reasonable limit (7.07%). For Rz parameter, however, the error was found to be larger than that of Ra parameter.

Table 5. Confirmation of the experiment

Response	Prediction from Eq.(1)	Experimental	Error (%)
Surface roughness of Ra (μm)	0.452	0.420	7.07
Surface roughness of Rz (μm)	2.912	2.53	13

4. CONCLUSIONS

The following conclusions were drawn in terms of the experimental and analytical results for the surface finish of hardened steels with coated ceramic tools.

1) The experimental results showed that the surface finish was highly influenced by the feed rate, followed by the depth of cut, but no significant effect was observed for the cutting sped and cutting fluid.
2) ANOVA indicated that the feed rate exerted a great effect on the surface finish of Ra at a contribution of 64%. However, the cutting speed,depth of cut and fluid had a neglecting effect towards the quality characteristics. A similar trend was obtained for Rz parameter.
3) Optimal process parameters, which minimize the surface finish of Ra was the factors of combinations of A_2, B_1, C_1 and D_2. That was, the experiment carried out at a speed of 120 m/min, 0.12 feed rate and 0.2 mm depth of cut when machining with lubricated conditions would lead to a minimum surface finish.

4) Besides, confirmation experiments were conducted to verify the optimal testing parameters. The difference between the predicted surface finish and measured surface finish varied between 7 and 13 % for Ra and Rz parameter, respectively.

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