

Statistical Analysis of the Effects of Machining Parameters and Workpiece Hardness on the Surface Finish of Machined Medium Carbon Steel

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The objective of this study is to ascertain the effect of machining parameters and workpiece hardness on surface roughness of machined components and to develop a better understanding of the effect of process parameters on the machined surface. Such an understanding can provide insight into the problems of controlling the finish of machined surfaces when the process parameters are adjusted to obtain a certain surface finish. The collected data were analyzed using parametric analyses of variance (ANOVA) with surface finish as the dependent variable and hardness of the workpiece material, cutting tool position from the surface of the clamping device (chuck), depth of cut, cutting velocity, and cutting feed as independent variables. The results showed that surface roughness is significantly affected by the workpiece hardness, cutting feed, cutting speed, depth of cut, cutting tool position from the chuck, and their interactions with each other. The results suggest that feed rate and cutting speed can be adjusted to produce a certain surface finish when the position of the cutting tool from the surface of a clamping device or the hardness of the workpiece is changed.

Keywords ANOVA, clamping device, clamping position, heat treatment, medium carbon steel, Pareto chart, surface finish, surface roughness

1. Introduction

The demand for high quality and fully automated production focuses attention on the surface condition of the product, especially the roughness of the machined surface, because of its effect on product appearance, function, and reliability. For these reasons, it is important to maintain consistent tolerances and surface finish.[1] Also, the quality of the machined surface is useful in diagnosing the stability of the machining process, where a deteriorating surface finish may indicate workpiece material nonhomogeneity, progressive tool wear, cutting tool chatter, *etc.*

The accelerated application of computer aided manufacturing to machining by the use of computer numerical control machine tools has focused on developing reliable machinery data systems, to ensure optimum production using expensive equipment. These computerized machinability data systems have been classified into two general types,[2] namely, the database system and the mathematical model system. The database system uses the collection and storage of large quantities of data from experiments, and the mathematical model attempts to predict the optimum con-ditions.[2]

Surface finish, in turn, is affected by a number of factors, such as cutting feed, cutting speed, depth of cut, cutting tool nose radius, cutting tool wear, vibration, *etc.* These factors have been studied by many investigators[3–11] on certain materials.

Researchers in this area attempt to develop models that can predict surface finish of a metal for a variety of machining conditions such as speed, feed, depth of cut, *etc.* Reliable models would not only simplify manufacturing process planning and control, but would also assist in optimizing machinability of materials.

The theoretical models to predict surface finish, while accounting for the effect of feed rate and cutting speed, have not considered the effect of tool position on the roughness of the machined surface. This was one of the main objectives of the present work. In addition, the interaction of this parameter with other machining parameters such as cutting speed, cutting feed, *etc.* was also studied. The effect of material hardness on the machined surface finished at different machining parameters and the interaction between the hardness of the workpiece and the above-mentioned parameters were also investigated.

2. Methodology

2.1 Workpiece Materials

Medium cold-drawn carbon steel (AISI 1060) in the form of bars was the workpiece material. The composition, element limits, and deoxidization practice were chosen according to the requirements of ANSI/ASME B94.55M-1985 standards. Table 1 shows the chemical composition of the selected medium carbon steel.

The steel was heat treated in order to develop four levels of hardness, including as received. The following heat treatments were used.

- Process annealing: The bars were heated to 550 °C for 2 h and then air cooled.

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- Normalizing: The bars were heated to 850 °C for 2 h and then air cooled.
- Full annealing: The bars were heated to 850 °C for 2 h and then cooled inside the furnace after turning it off. Table 2 shows the hardness values resulting from the above-mentioned heat treatments.

2.2 Equipment

- A 40 HP heavy duty Colchester Master 2500 turning machine.
- Digital surtronic 3P instrument for arithmetical roughness average (R_a).
- Tinius-Olsen Brinell hardness testing machine.

2.3 Experimental Design

A complete set of experiments has been carried out. For each hardness specified in Table 2, four feed rates (0.05, 0.16, 0.25, and 0.4 mm/rev), four cutting speeds (36, 49, 88, and 119 m/min), four depths of cut (0.1, 0.2, 0.4, and 0.6 mm), and three cutting tool positions (20, 30, and 40 cm) were used as the independent variables. Surface roughness R_a measured in micrometers was the response variable. Several variables were put under close control, including the machine on which turning was performed (the same machine was used for all experimental work), the operator (the same operator machined all specimens), and constant cutting tool angles. The surface roughness data were collected randomly for each of the 768 machining conditions defined by the levels of independent variables (four hardness × four cutting feeds × four cutting speeds × four depths of cut × three cutting tool positions).

Table 1 The chemical composition of the selected medium carbon steel

C	S	Al	Si	Ni	Cr	Mn
0.6	0.0107	0.08	0.44	0.32	0.27	0.59

Table 2 The hardness of the workpiece material used in the experiment

Thermal treatment	Brinell hardness (HB)
As received	247
Process annealing	218
Normalizing	192
Full annealing	165

2.4 Results and Discussion

Tables 3 to 6 give the variations in average surface finish with cutting speed, feed, cutting tool position, and depth of cut.

The collected data were analyzed using parametric analyses of variance (ANOVA) with surface finish as the dependent variable and hardness of the workpiece material, cutting tool position from the surface of clamping device (chuck), depth of cut, cutting velocity and cutting feed as independent variables. The ANOVA model was modified to include the main effects of the independent variables and up to two-variable interactions only. The significance level was based on the P-value from ANOVA[12] as

$$\textit{Insignificant if } P > 0.10$$
$$\textit{Mildly significant if } 0.05 < P < 0.10$$
and
$$\textit{Significant if } P < 0.05$$

The analysis indicated that all main factors and their interactions (except the interaction between the cutting tool position and the depth of cut) were highly significant ($P < 0.05$). This

Table 3 Average values of measured surface finish (micrometers) for 165 HB workpiece

Depth of cut	Feed, mm/rev	Cutting tool position from the surface of the clamping device, P = 20 cm Cutting speed, m/min				Cutting tool position from the surface of the clamping device, P = 30 cm Cutting speed, m/min				Cutting tool position from the surface of the clamping device, P = 40 cm Cutting speed, m/min			
		36	49	88	119	36	49	88	119	36	49	88	119
0.1 mm	0.05	4.00	3.50	3.20	2.90	4.26	3.79	3.65	3.45	4.46	4.03	4.06	3.96
	0.16	5.50	4.90	4.20	3.80	5.85	5.31	4.80	4.52	6.13	5.65	5.33	5.18
	0.25	8.80	7.00	6.00	5.70	9.36	7.58	6.85	6.77	9.81	8.07	7.61	7.78
	0.40	14.0	11.0	8.50	7.90	14.90	12.0	9.71	9.39	15.6	13.0	10.8	10.8
0.2 mm	0.05	4.40	3.85	3.52	3.19	4.68	4.17	4.02	3.79	4.91	4.44	4.46	4.35
	0.16	6.05	5.39	4.62	4.18	6.44	5.84	5.28	4.97	6.75	6.21	5.86	5.70
	0.25	11.3	9.00	6.90	6.20	12.02	9.75	7.88	7.37	12.6	10.4	8.75	8.46
	0.40	15.5	13.2	10.5	11.0	16.49	14.3	12.0	13.1	17.3	15.2	13.3	15.1
0.4 mm	0.05	4.30	4.07	3.72	3.37	4.70	4.41	4.25	4.01	5.10	4.69	4.72	4.60
	0.16	6.37	5.68	4.88	4.42	6.78	6.16	5.57	5.25	7.10	6.55	6.19	6.02
	0.25	12.0	9.30	7.00	6.30	12.77	10.1	7.99	7.49	13.4	10.7	8.88	8.59
	0.40	16.5	14.7	11.5	9.40	17.56	15.9	13.1	11.2	18.4	16.9	14.6	12.8
0.6 mm	0.05	4.78	4.27	3.92	3.52	5.09	4.63	4.48	4.19	5.33	4.92	4.97	4.80
	0.16	6.69	5.96	5.00	4.58	7.12	6.45	5.71	5.44	7.46	6.86	6.35	6.25
	0.25	10.6	10.1	7.20	6.60	11.28	10.9	8.22	7.84	11.8	11.6	9.13	9.00
	0.40	17.0	14.6	11.8	10.0	18.09	15.8	13.5	11.9	18.9	16.8	15.0	13.6

Table 4 Average values of measured surface finish (micrometers) for 192 HB workpiece

		Cutting tool position from the surface of the clamping device, $P = 20$ cm Cutting speed, m/min				Cutting tool position from the surface of the clamping device, $P = 30$ cm Cutting speed, m/min				Cutting tool position from the surface of the clamping device, $P = 40$ cm Cutting speed, m/min			
Depth of cut	Feed, mm/rev	36	49	88	119	36	49	88	119	36	49	88	119
0.1 mm	0.05	3.56	3.14	2.88	2.63	3.77	3.39	3.27	3.09	3.94	3.59	3.61	3.52
	0.16	4.79	4.30	3.73	3.39	5.07	4.64	4.22	3.99	5.30	4.91	4.65	4.53
	0.25	7.36	5.98	5.19	4.95	7.79	6.43	5.86	5.80	8.12	6.81	6.45	6.58
	0.40	11.1	8.99	7.14	6.68	11.73	9.71	8.04	7.80	12.2	10.4	8.83	8.83
0.2 mm	0.05	3.89	3.43	3.16	2.88	4.12	3.70	9.73	3.39	4.31	3.92	3.95	3.85
	0.16	5.23	4.70	4.07	3.71	5.54	5.06	12.8	4.36	5.78	5.36	5.08	4.95
	0.25	9.21	7.51	5.90	5.35	9.73	4.12	6.66	6.27	10.1	8.53	7.33	7.10
	0.40	12.1	10.5	8.63	8.99	12.80	5.54	9.70	10.4	13.3	11.9	10.6	11.80
0.4 mm	0.05	3.81	3.62	3.33	3.03	4.14	3.90	3.77	3.57	4.47	4.13	4.16	4.06
	0.16	5.48	4.94	4.28	3.90	5.81	5.32	4.85	4.59	6.06	5.63	5.34	5.21
	0.25	9.71	7.74	5.98	5.43	10.26	8.31	6.75	6.36	10.7	8.79	7.42	7.21
	0.40	12.8	11.6	9.35	7.81	13.50	12.4	10.5	9.12	14.0	13.1	11.5	10.29
0.6 mm	0.05	4.21	3.79	3.49	3.16	4.46	4.08	3.96	3.71	4.65	4.32	4.36	4.22
	0.16	5.74	5.15	4.39	4.04	6.07	5.55	4.96	4.74	6.34	5.87	5.47	5.39
	0.25	8.70	8.33	6.14	5.67	9.19	8.95	6.92	6.63	9.58	9.45	7.61	7.52
	0.40	13.1	11.5	9.57	8.26	13.85	12.3	10.7	9.63	14.4	13.0	11.8	10.87

Table 5 Average values of measured surface finish (micrometers) for 218 HB workpiece

		Cutting tool position from the surface of the clamping device, $P = 20$ cm Cutting speed, m/min				Cutting tool position from the surface of the clamping device, $P = 30$ cm Cutting speed, m/min				Cutting tool position from the surface of the clamping device, $P = 40$ cm Cutting speed, m/min			
Depth of cut	Feed, mm/rev	36	49	88	119	36	49	88	119	36	49	88	119
0.1 mm	0.05	3.18	2.83	2.61	2.39	3.36	3.04	2.94	2.79	3.50	3.21	3.22	3.15
	0.16	4.19	3.80	3.32	3.04	4.42	4.07	3.73	3.54	4.60	4.29	4.08	3.99
	0.25	6.20	5.14	4.52	4.32	6.52	5.49	5.05	5.00	6.77	5.78	5.51	5.61
	0.40	8.91	7.41	6.03	5.68	9.33	7.93	6.71	6.54	9.66	8.43	7.29	7.29
0.2 mm	0.05	3.46	3.08	2.84	2.60	3.65	3.30	3.20	3.04	3.80	3.48	3.50	3.43
	0.16	4.55	4.12	3.61	3.31	4.79	4.41	4.05	3.84	4.99	4.65	4.43	4.33
	0.25	7.57	6.32	5.08	4.64	7.94	6.74	5.67	5.36	8.23	7.08	6.18	6.01
	0.40	9.60	8.52	7.14	7.41	10.05	9.05	7.92	8.46	10.4	9.47	8.58	9.38
0.4 mm	0.05	3.39	3.23	2.99	2.74	3.66	3.47	3.36	3.19	3.93	3.66	3.68	3.60
	0.16	4.75	4.31	3.78	3.47	5.00	4.62	4.24	4.03	5.20	4.86	4.63	4.53
	0.25	7.93	6.49	5.14	4.71	8.31	6.91	5.74	5.44	8.61	7.26	6.25	6.09
	0.40	10.0	9.24	7.67	6.54	10.50	9.80	8.49	7.50	10.9	10.2	9.18	8.34
0.6 mm	0.05	3.72	3.37	3.13	2.84	3.92	3.61	3.51	3.31	4.08	3.81	3.85	3.73
	0.16	4.95	4.49	3.87	3.58	5.21	4.80	4.33	4.16	5.42	5.06	4.74	4.67
	0.25	7.20	6.93	5.26	4.89	7.55	7.38	5.87	5.65	7.84	7.74	6.39	6.32
	0.40	10.3	9.19	7.82	6.87	10.73	9.75	8.66	7.87	11.1	10.2	9.36	8.74

can be seen in Fig. 1, which shows the Pareto chart of standardized effects, indicating the main effects and interaction for surface finish.

The numerical estimates of the effects indicate that the effect of feed is the largest (90.1264) and has positive direction. The positive direction means that the surface finish deteriorated with increasing the cutting feed. Figure 2 shows the main effect of the increase in the cutting feed on the surface roughness. The changes in surface roughness profiles are shown in Fig. 3 under the following machining conditions (hardness of the workpiece = 247 HB, depth of cut = 0.6 mm, cutting tool position from the surface of the clamping device, $P = 40$ cm, and cutting speed = 119 m/min). This is due to the increase in distance between the successive grooves made by the tool during the cutting action, as the cutting feed increases.

Figure 1 shows the effect of hardness of workpiece material (−47.2543). The negative direction means that increasing the workpiece hardness improves the surface finish. It is generally well known that an increase in hardness improves machinability. This is clearly confirmed in Fig. 4.

The cutting speed also has a negative value, which indicates that increasing the cutting speed improves the surface finish, as shown in Fig. 5. This may be due to the continuous reduction in the build-up edge formation as the cutting speed increases.

The interaction between the cutting feed and workpiece hardness significantly affects the surface roughness, as shown

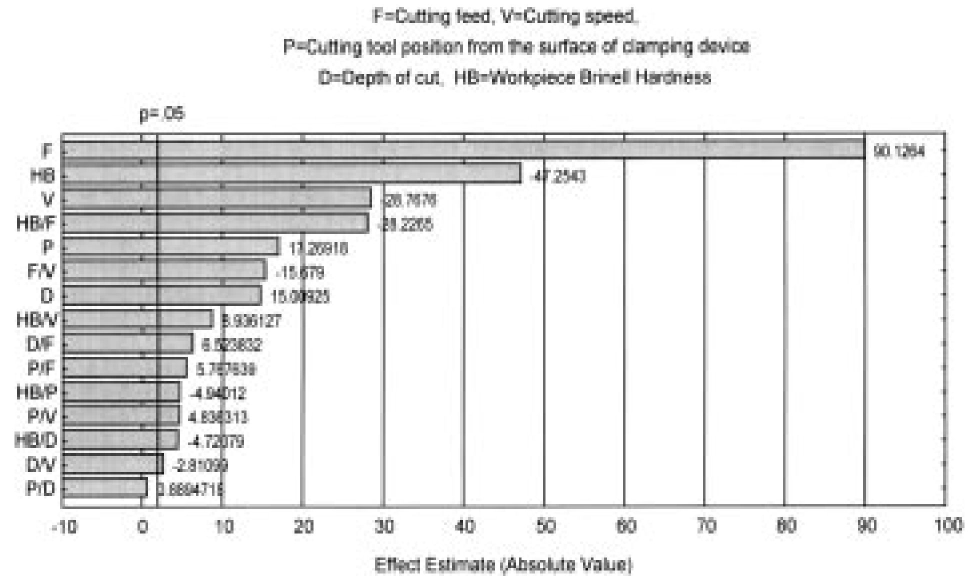

Fig. 1 Pareto chart of standardized effects for surface roughness R_a showing significant factors and interactions

Table 6 Average values of measured surface finish (micrometers) for 247 HB workpiece

		Cutting tool position from the surface of the clamping device, $P = 20$ cm Cutting speed, m/min				Cutting tool position from the surface of the clamping device, $P = 30$ cm Cutting speed, m/min				Cutting tool position from the surface of the clamping device, $P = 40$ cm Cutting speed, m/min			
Depth of cut	**Feed, mm/rev**	**36**	**49**	**88**	**119**	**36**	**49**	**88**	**119**	**36**	**49**	**88**	**119**
0.1 mm	0.05	2.88	2.58	2.39	2.20	3.03	2.75	2.67	2.54	3.15	2.90	2.91	2.85
	0.16	3.73	3.40	3.00	2.76	3.91	3.62	3.34	3.18	4.06	3.80	3.63	3.55
	0.25	5.33	4.49	3.99	3.83	5.57	4.77	4.44	4.38	5.76	5.00	4.79	4.86
	0.40	7.32	6.24	5.20	4.92	7.62	6.62	5.72	5.58	7.84	6.98	6.15	6.15
0.2 mm	0.05	3.11	2.79	2.59	2.38	3.28	2.98	2.89	2.75	3.40	3.14	3.15	3.09
	0.16	4.02	3.67	3.24	2.99	4.21	3.91	3.61	3.44	4.37	4.10	3.92	3.83
	0.25	6.36	5.42	4.44	4.09	6.63	5.74	4.91	4.67	6.84	5.99	5.31	5.18
	0.40	7.81	7.05	6.04	6.24	8.11	7.42	6.62	7.01	8.33	7.72	7.09	7.65
0.4 mm	0.05	3.06	2.92	2.71	2.50	3.29	3.12	3.03	2.89	3.51	3.28	3.30	3.23
	0.16	4.18	3.82	3.38	3.12	4.38	4.07	3.76	3.59	4.54	4.27	4.09	4.00
	0.25	6.62	5.55	4.49	4.14	6.90	5.87	4.97	4.73	7.11	6.13	5.36	5.24
	0.40	8.11	7.55	6.43	5.59	8.41	7.94	7.03	6.31	8.64	8.24	7.52	6.92
0.6 mm	0.05	3.33	3.04	2.83	2.59	3.50	3.24	3.16	2.99	3.64	3.41	3.44	3.34
	0.16	4.34	3.97	3.46	3.22	4.55	4.22	3.84	3.69	4.72	4.43	4.17	4.12
	0.25	6.08	5.88	4.59	4.30	6.35	6.22	5.07	4.90	6.55	6.49	5.47	5.42
	0.40	8.25	7.52	6.55	5.84	8.56	7.90	7.15	6.58	8.79	8.20	7.64	7.20

in Fig. 6. The figure shows that, with the increase in hardness, the surface finish is improved, and an increase in feed decreases the surface finish, as mentioned earlier. The interaction also suggests that, to obtain a certain surface finish and maximum metal removal, it is preferable to use a high cutting feed associated with high workpiece hardness.

The main effect of the cutting tool position from the chuck on the surface finish is shown in Fig. 7. Increasing the cutting tool position from the workpiece-clamping device deteriorates the surface finish. This can be explained by the increase in the chattering of the cutting tool due to the long distance between the tool tip and the surface of the clamping device (chuck) of the turning machine.

The interaction between the cutting feed and cutting speed significantly affects the surface roughness, as shown in Fig. 8. The figure shows that increasing the cutting speed improves the surface finish as the cutting feed decreases. This supports the earlier discussion about the effect of decreasing cutting speed on the surface roughness of the machined workpieces.

The effect of the depth of cut is less significant on the surface finish, as shown in Fig. 9. Generally, it can be said that increasing the depth of cut deteriorates the surface finish. This can be explained by the increase in the cutting temperature due to the increase in the shear zone, chip-tool interface, and workpiece-tool interface.

The interaction between workpiece hardness and cutting speed affects the surface roughness, as shown in Fig. 10, but the degree of interaction is less than the interaction between the workpiece hardness and cutting feed. It can be observed from Fig. 10 that increasing the cutting speed improves the surface finish as the workpiece hardness increases. This supports the discussion above about the effect of hardness and cutting speed on surface roughness of the machined workpieces. The interaction also suggests that, to get a desired surface finish and maximum metal removal, it is preferable to use high cutting speed associated with high workpiece hardness.

The interaction between the depth of cut and cutting feed is less significant, as shown in Fig. 11. The interaction reveals that increasing the cutting speed and increasing the depth of cut deteriorates the surface finish. This figure also shows that, at high cutting speeds, the effect of depth of cut is more profound because of the possible increase in cutting temperature due to the increase in depth of cut and cutting feed.

The interaction effect between the cutting feed and cutting tool position is not very large, as shown in Fig. 12. However, the increases of cutting feed and tool position from the clamping device deteriorate the surface finish. At high cutting feed, it seems from the figure that the effect of tool position is more

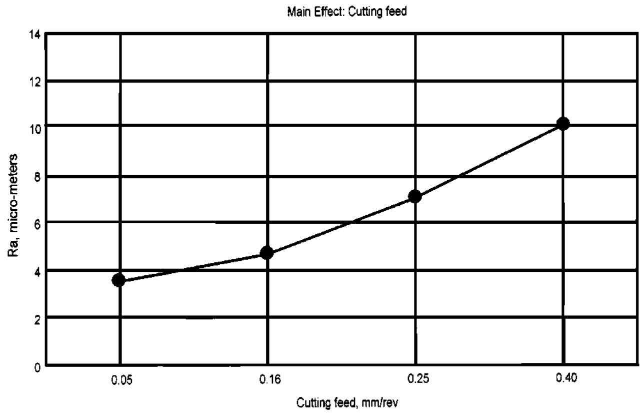

Fig. 2 Main effect of cutting feed on surface roughness

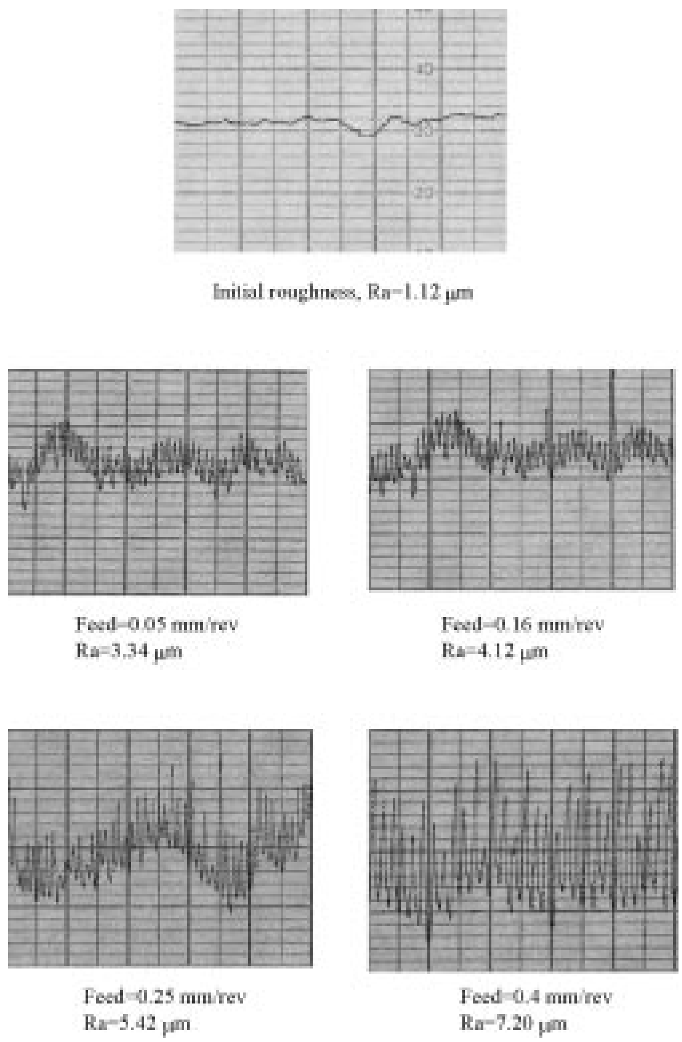

Fig. 3 The effect of cutting feed on surface roughness profile of the machined workpiece (hardness of the workpiece = 247 HB, depth of cut = 0.6 mm, cutting tool position from the surface of the clamping device, P = 40 cm, and cutting speed = 119 m/min)

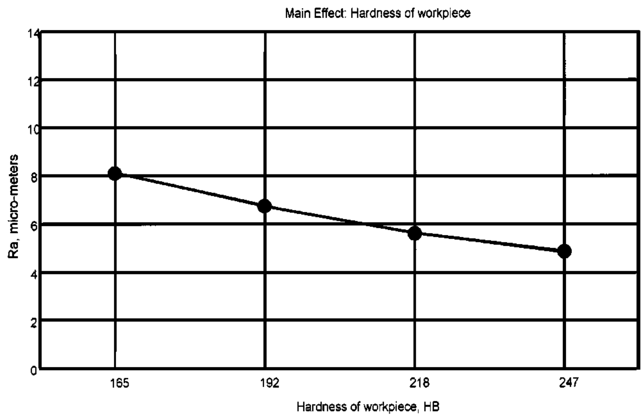

Fig. 4 Main effect of workpiece hardness on surface roughness

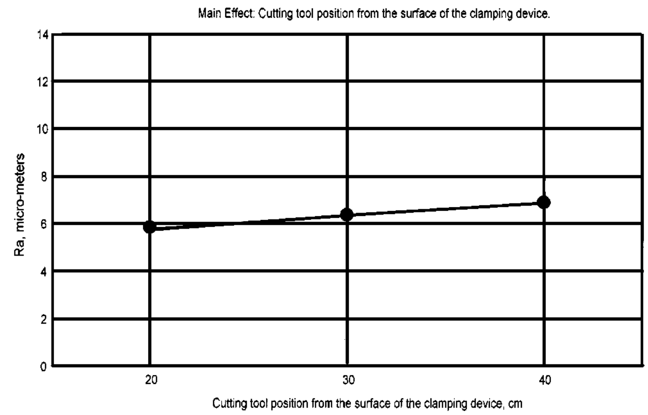

Fig. 7 Main effect of cutting tool position from the surface of clamping device on surface roughness

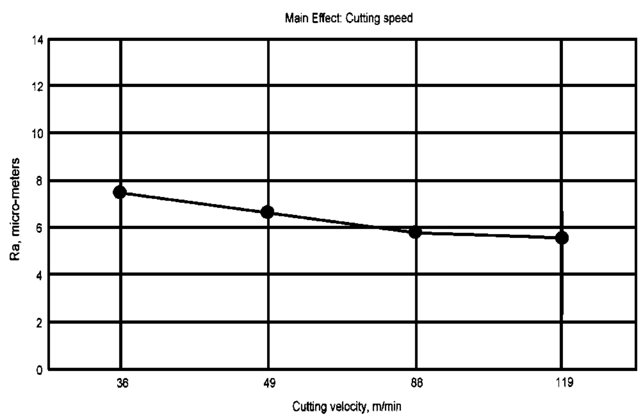

Fig. 5 Main effect of cutting velocity on surface roughness

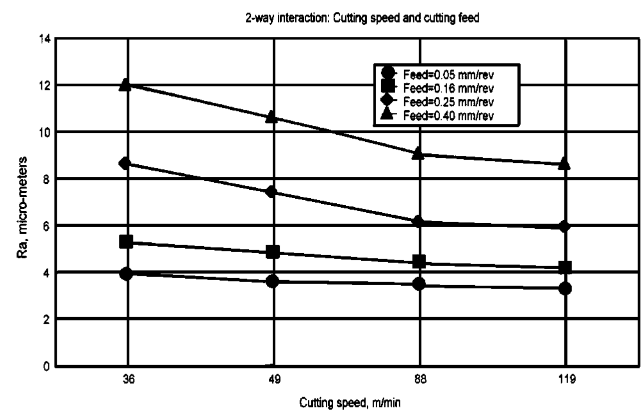

Fig. 8 Interaction effect between cutting speed and cutting feed on surface roughness

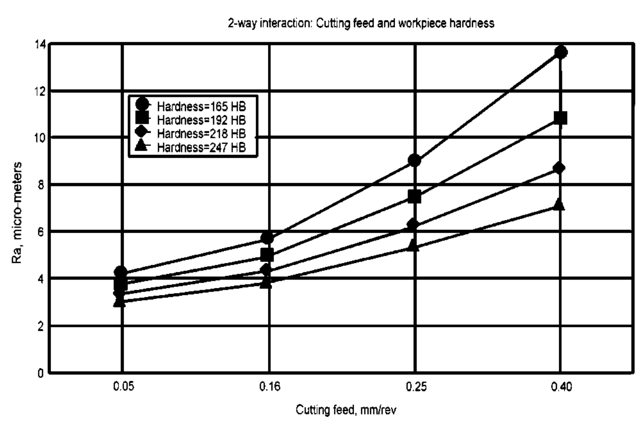

Fig. 6 Interaction effect between cutting feed and workpiece hardness on surface roughness

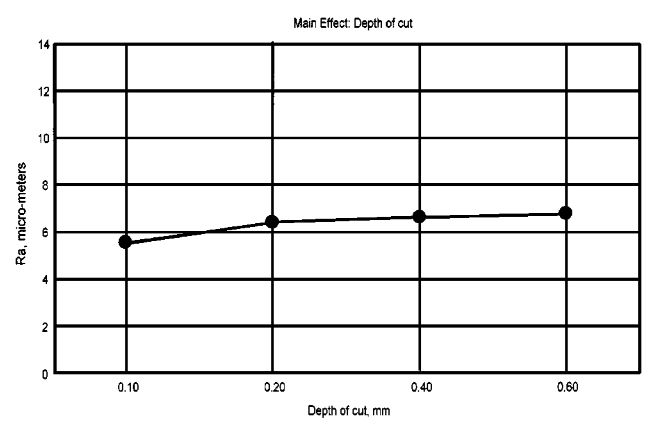

Fig. 9 Main effect of depth of cut on surface roughness

significant at high cutting feed because of the increase in the chattering effect as the cutting feed increases.

The interaction effect between the cutting speed and cutting tool position from the clamping device is not very large, as shown in Fig. 13. Generally, the increase in cutting speed and the decrease of the cutting tool position improve the surface finish. This can be explained by the reduction in the chattering of the cutting tool caused by the increase of the cutting speed due to the decrease of the cutting tool position from the clamping device.

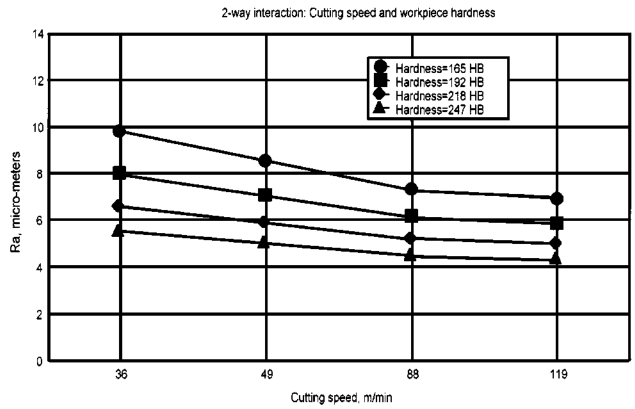

Fig. 10 Interaction effect between cutting speed and workpiece hardness on surface roughness

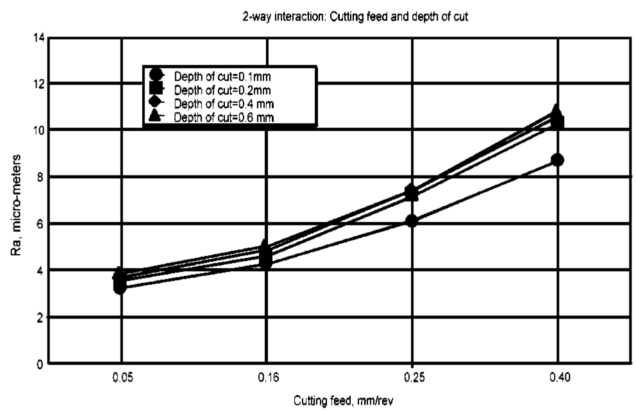

Fig. 11 Interaction effect between depth of cut and cutting feed on surface roughness

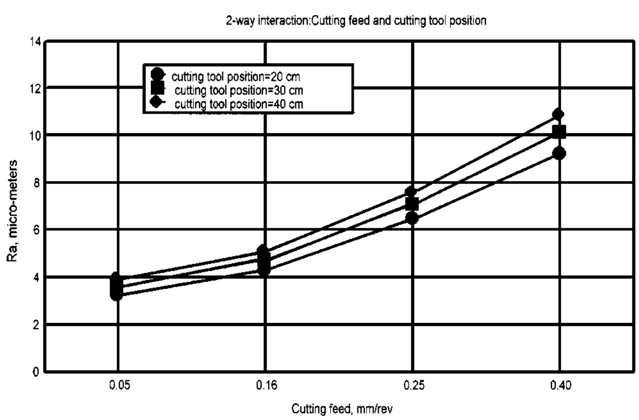

Fig. 12 Interaction effect between cutting feed and cutting tool position on surface roughness

The interaction effects between the cutting tool position and workpiece hardness or between the depth of cut and workpiece hardness or between cutting speed and depth of cut seem to have little affect on surface roughness, as can be seen in Fig. 14, 15, and 16, respectively.

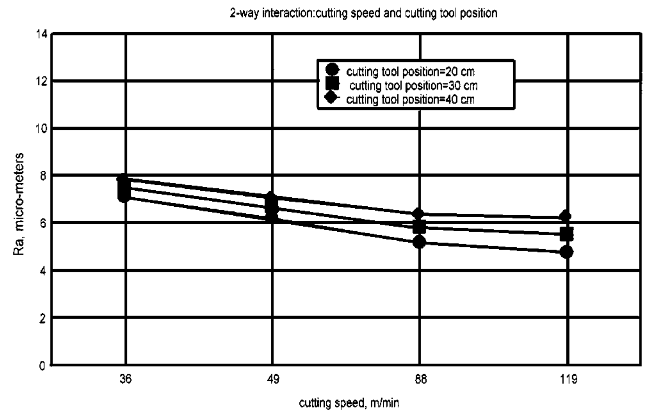

Fig. 13 Interaction effect between cutting speed and cutting tool position on surface roughness

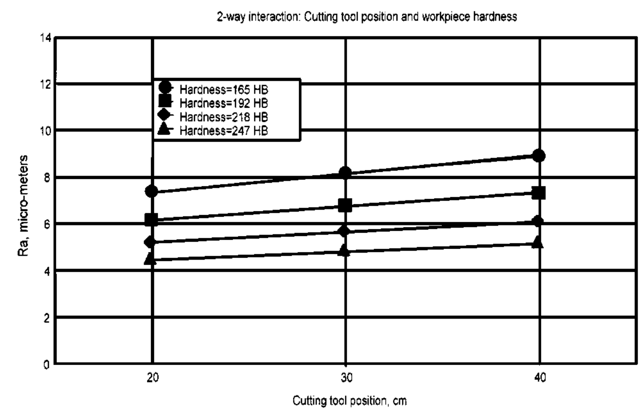

Fig. 14 Interaction effect between cutting tool position and workpiece hardness on surface roughness

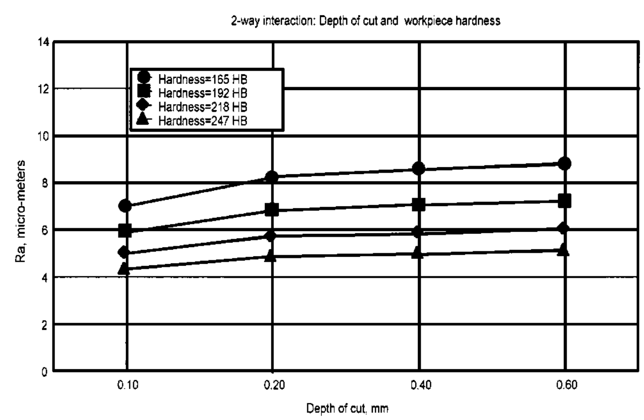

Fig. 15 Interaction effect between the depth of cut and workpiece hardness on surface roughness

3. Conclusions

The conclusions extracted from the present investigation are as follows.

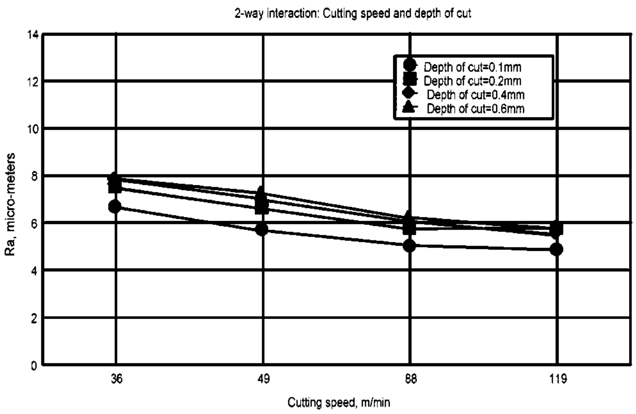

Fig. 16 Interaction effect between cutting speed and depth of cut on surface roughness

- The machining parameters investigated significantly influenced the surface finish of the machined workpiece. In general, the effect of feed was more profound than the effect of other parameters such as workpiece hardness, cutting velocity, depth of cut, and cutting tool position.
- The surface finish generally improves with the cutting speed and workpiece hardness and deteriorates with increase in feed, depth of cut, and cutting tool position.
- The increase of the cutting tool position from the surface of the clamping device significantly deteriorates the surface finish.
- The effect of cutting speed and cutting feed on the surface finish of the machined workpiece largely depends upon the hardness of the material being turned.
- The most important interactions that affect surface roughness of machined carbon steel were between the hardness of the workpiece and the cutting feed, between the cutting feed and the cutting velocity, and between the workpiece hardness and the cutting speed. The interaction effect between the cutting tool position and the workpiece hardness or between the depth of cut and the workpiece hardness or between the cutting speed and the depth of cut seems to be of little significance on the surface roughness.

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