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Optimization of Cutting Parameters in Hard Turning of AISI H10A Steel under Minimum Quantity Lubrication

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Abstract

In this study, influences of cutting parameters in hard turning of hot work tool steel by applying minimum quantity lubrication (MQL) were investigated and optimized by using Taguchi methodology. Firstly, the machinability experiments on hardened AISI H10A hot work tool steel with CBN inserts were performed under the MQL condition. The experiments were carried out by Taguchi's L9 orthogonal array. The machinability of AISI H10A steel were evaluated in terms of average surface roughness (Ra) and main cutting force (Fc). The analysis of variance (ANOVA) was applied to determine the effects of cutting parameters (cutting speed, feed rate and depth of cut) on surface roughness and cutting force. It was observed that surface roughness and cutting force increased with increasing feed rate and depth of cut in machining by applying MQL with uncoated CBN inserts. Depth of cut was determined as the most important parameter on surface roughness with 66.57% PCR while feed rate was determined on cutting force with 50.68% PCR. On the other hand, optimum cutting parameters for surface roughness and cutting force were found at different levels as a result of Taguchi optimization.

Key words

AISI H10A, MQL, optimization, cutting force, surface roughness

1. INTRODUCTION

Hot work tool steels having high temperature strength, high toughness and resistance to thermal fatigue and shock are preferred frequently in many industrial applications. The chromium hot work steels are widely used for extrusion of aluminum, die casting of light metals and steel forging applications [1]. On the other hand, these steels due to chemical composition, microstructure, inclusions and thermo-mechanical properties are difficult to machine. When the die is subjected to heat treatment, some distortion usually occurs. Thus, machining allowance is left on the die prior to hardening in order to overcome these negativities as well as to ensure measurement and surface integrity. It is possible to adjust the die after the hardening and tempering by finish machining processes such as grinding, hard machining, etc.

Hard turning are mainly concentrated on the tool materials cost and the effect of the cutting conditions on machinability criteria. The machining of hardened steels using cubic boron nitride and ceramic tool are commonly known as a best replacement instead of grinding in order to reduce the tooling time and machining cost, keep off the lubrication [2]. Also, it is very difficult to develop a comprehensive model with related to any machinability criteria involving all machining conditions due to contain many factors. The machinability criteria such as cutting forces, surface roughness, tool life, dimensional accuracy can be significantly affected by machining parameters, mechanical properties of workpiece material, rigidity of machine tools, tool material and coolant technique [3,4].

The control of the machinability criteria can be primarily provided by choosing appropriate values of cutting speed, feed rate and depth of cut in hard turning [5]. However, unsuitable cutting parameters have negative effects on the machining outputs such as machining time, cost. In this context, design of experiment and analysis for machining process, then optimization of machining output is great importance with regards to decrease machining cost [6]. Also, some scientists observed that there is a disagreement between the researchers in terms of the use of coolants or lubricants in hard turning. Thus, it is required to identify eco-friendly alternatives to conventional cutting fluids during hard turning as can be specified in many investigations [7]. Recently, scientists used nanoparticles in conventional lubricants owing to its remarkable improvement in thermo-mechanical, and heat transfer capabilities, decrease the friction coefficient and wear effect to enhance the efficiency and reliability of machine tools [8].

Newly, there are performed numerous experimental and statistical studies which are based on design and analysis of experiment methods to determine the effects of cutting conditions on machinability criteria. Aouici et al. conducted response surface methodology (RSM) in hard turning of DIN 1.2343 steel with CBN tool in order to obtain mathematical models for the cutting forces and surface roughness. They specified that the depth of cut and workpiece hardness are the most important factor on cutting forces while the feed rate and workpiece hardness have the most significant for surface roughness [9]. Boy et al. addressed on optimizing the cutting conditions to minimize the surface roughness, inner-diameter error and roundness in bearing rings produced by hard turning of AISI 52100 steel with coated CBN insert. The analysis of variance results indicated that the feed rate is the main factor for the surface roughness while the cutting speed is the major factor for the roundness and inner-diameter error [10]. Kaçal investigated the cutting performance of ceramic insert in terms of surface roughness and tool wear in turning of hardened PMD 23 steel with three different cutting speeds, feed rates and depth of cuts. The experimental results indicated that feed rate is the most significant factor affecting Ra followed by depth of cut [11]. Islam investigated the surface roughness and dimensional accuracy properties (diameter error and circularity) via dry, wet and minimum quantity lubrication turning processes applied to different materials. The author indicated that surface roughness and dimensional values are affected by different cooling methods and the best result is obtained with MQL application [12]. Sarıkaya and Güllü focused on the use of the Taguchi based grey relation analysis to optimize the MQL process parameters such as cutting fluid, flow rate and cutting speed in terms of tool wear forms and surface roughness during the turning of Haynes 25 super alloy. According to the ANOVA results, the contribution percentage of process parameters were found as the cutting fluid, fluid flow rate and cutting speed, respectively [13]. Paul et al. examined parameters of minimum fluid application for minimizing surface roughness, flank wear, cutting force, tool vibration and cutting temperature in machining of AISI 4340 steel. The authors emphasized that tool vibration reduced in hard turning with minimal fluid application and the better cutting performance was provided as compared with dry turning and wet turning where a commercial cutting fluid was applied at a rate of 5 l/min [14]. Mia et al. investigated surface roughness during turning of hardened steel of 600 BHN with uncoated carbide tool under MQL application. The researchers stated that the cutting speed is insignificant factor surface roughness while feed rate is important factor for roughness [15].

2. MATERIAL AND METHOD

2.1. Material and Equipment

The workpiece material was used AISI H10A tool steel with the following chemical composition: 0.32% C; 0.40% Mn; 2.75% Co; 2.95% Cr; 2.8% Mo; 0.55% V and balance Fe. The material is a hot work tool steel having high toughness, high thermal shock resistant and high wear resistance in high temperatures. The hardness of AISI H10A workpiece was increased to 54-55 HRC with vacuumed hardening method. CNGA120404 coded uncoated CBN (KB1610) inserts and PCLNR 2525M12 coded tool holder produced by Kenna Metal Company were used in hard turning experiments. Hard turning experiments were carried out on Johnford TC 35 CNC having 20 HP motor under minimum quantity lubricant (MQL) cutting condition. UFB20-Basic cooling system branded SKF was preferred as MQL applicator. The Lubri-Oil was used as lubricant type because of AISI H10A steel. It was decided after preliminary experiments used MQL that the flow rate should be 16.25 ml/min.

The main cutting force (*Fc*) and average surface roughness (*Ra*) were considered on as the machinability criteria of AISI H10A steel. The cutting forces were measured by using Kistler 9257B type piezoelectric dynamometer during turning of workpiece material. Mahr Perthometer M1 type roughness device was used to measure surface roughness in hard turning experiments. The surface roughness values were taken into account in evaluating the roughness of machined surface. The experiments were repeated two times and evaluations were done by taking arithmetic mean of surface roughness.

2.2. Experimental Design and Optimization

The cutting parameters directly effecting machinability criteria were determined in experimental design according to Taguchi method. For this purpose, three factors were chosen as depth of cut (a), feed rate (f) and cutting speed (V) (seen Table 1). The levels of these parameters were preferred by reference to the recommendation of cutting tool firm and researches on hard turning. Taguchi L_9 orthogonal array was used for experimental design in terms of the factor and levels. Moreover, the experiments conducted with uncoated CBN tools were performed in MQL cutting condition.

Table 1. Factors and their levels

Factors	Unit	Level 1	Level 2	Level 3
Depth of cut (a)	mm	0.1	0.2	0.3
Feed rate (f)	mm/rev	0.05	0.1	0.15
Cutting speed (V)	m/min	100	150	200

In the light of experimental results, the effects of factors on the main cutting force (*Fc*) and average surface roughness (*Ra*) were determined by analysis of variance (ANOVA) with 95% confidence level. Finally, cutting parameters for *Fc* and *Ra* were optimized based on Taguchi method. Therefore, the-smaller-the-better approach were applied due to desire of minimum Fc and Ra which is selected as performance characteristic in hard turning experiments. The cutting parameters giving optimum cutting force and surface roughness were determined in optimization study according to *S/N* ratio. The *S/N* ratios for the-smaller-the-better approach is calculated as follows [16].

$$S/N = -10\cdot\log\left(\frac{1}{n}\cdot\sum_{i=1}^{n} y_i^2\right) \qquad (1)$$

Here, y_i is the i_{th} measure of the experimental results in a run and *n* gives the number of measurements in each experiment. The function '-log' is a monotonically decreasing one, it means that we should maximize the *S/N* ratio. Statistical analyses and optimization studies were performed by Minitab software.

3. RESULTS AND DISCUSSION

3.1. Evaluation of Experimental Results

The variations of main cutting force and surface roughness values obtained with uncoated CBN tools in MQL cutting condition are given in separate graphs. Variations of Fc and Ra depending on feed rate (f), cutting speed (V) and depth of cut (a) are shown in Figure 1 and 2, respectively.

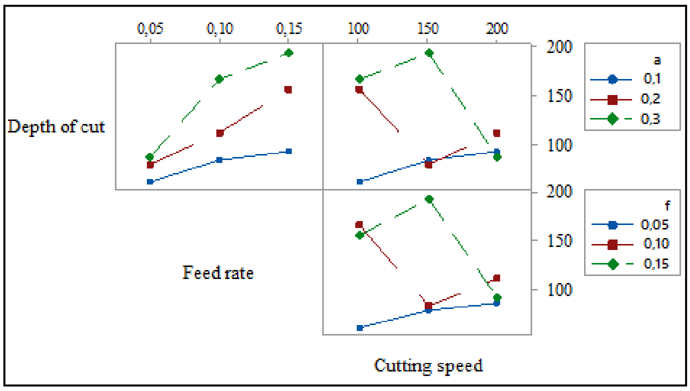

Figure 1. Variations of Fc in MQL cutting condition.

As can be seen from Figure 1, it was observed that main cutting force (*Fc*) generally increase with increasing feed rate and depth of cut. It was attracted from Figure 1 that the force values have irregularities in terms of cutting speed-depth of cut and cutting speed-feed rate interactions. This can be attributed with design of experiment that distribution of cutting speed is complicated in L_9 orthogonal array. The lowest surface roughness value was obtained as 62.73 N with feed rate of 0.05 mm/rev, cutting depth of 0.1 mm and cutting speed of 100 m/min in MQL cutting condition with uncoated CBN inserts.

Average surface roughness (*Ra*) values increase with increasing feed rate and depth of cut (seen Fig.2). In a similar way, it was determined that *Ra* values does not decrease with increasing cutting speed because of hybrid experimental design. The lowest surface roughness value was obtained as 0.139 µm with the lowest feed rate, depth of cut and cutting speed in MQL cutting conditions with uncoated CBN inserts. The highest surface roughness was obtained as 0.36 µm with feed rate of 0.15 mm/rev, depth of cut of 0.3 mm and cutting speed of 150 m/min.

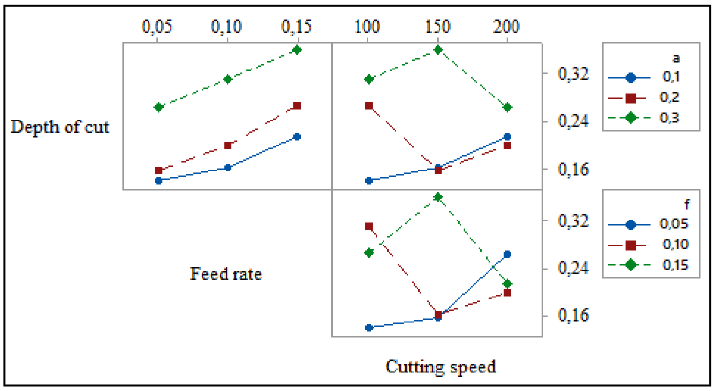

Figure 2. Variations of Ra in MQL cutting condition.

ANOVA was performed to determine the effectiveness of cutting parameters on main cutting force and average surface roughness during machining with uncoated CBN insert of AISI H10A hot work tool steel under minimum quantity lubrication (MQL) cutting environment. The results of ANOVA analysis of the cutting force and the surface roughness are presented in Tables 2 and 3, respectively.

Table 2. ANOVA results for cutting force

Factor	DF	SS	MS	F-ratio	P-value	PCR (%)
Depth of cut	2	39.1134	19.5567	114.24	0.009	43.27
Feed rate	2	45.7484	22.8742	133.62	0.007	50.68
Cutting speed	2	4.3925	2.1962	12.83	0.072	4.52
Residual error	2	0.3424	0.1712			1.53
Total	8	89.5966				100

DF: Degrees of freedom; SS: Sequential sum of squares; MS: Mean sum of squares

Table 3. ANOVA results for surface roughness

Factor	DF	SS	MS	F-ratio	P-value	PCR (%)
Depth of cut	2	44.2369	22.1185	201.57	0.005	66.57
Feed rate	2	20.7335	10.3668	94.47	0.000	31.03
Cutting speed	2	0.9312	0.4656	4.24	0.191	1.08
Residual error	2	0.2195	0.1097			1.32
Total	8	66.1211				100

DF: Degrees of freedom; SS: Sequential sum of squares; MS: Mean sum of squares

P value should be lower than 0.05 in 95% confidence level in order to determine that any parameter acting on the cutting force or surface roughness is effective on them. The feed rate (f) was the most important parameter affecting the cutting force with a PCR of 50.68% while the most significant parameter for surface roughness was obtained as depth of cut (a) with a PCR of 66.57%, as can be seen from Table 2 and 3. The other statistically significant parameters on *Fc* and *Ra* are depth of cut and feed rate with PCR of 43.27% and 31.03%, respectively.

3.2. Optimization with Taguchi Method

The main cutting force and surface roughness values were obtained as a result of hard turning experiments performed based on the Taguchi L_9 orthogonal array. According to Taguchi method, the experimental results have been transformed into *S/N* ratios to measure the quality characteristics diverging from the desired value. The *S/N* ratio is the ratio of the mean (signal) to the standard deviation (noise). In the present study, *S/N* ratio is calculated as the logarithmic transformation of the loss function by using the-smaller-the-better approach as minimum values of *Fc* and *Ra* is required. The experimental results and *S/N* ratios is calculated by using Eq. (1) for *Fc* and *Ra* are shown in Table 4.

The mean values of *S/N* ratios (η) of the factors for each of the levels were determined by Equation (1). Figure 3 and Figure 4 shows the graphic of the η values for main cutting force and surface roughness, respectively. Regardless of category of the performance characteristics, a maximum η value corresponds to a better performance according to Taguchi method. Therefore, the optimal level of the cutting parameters is the level with the maximum η value. As can be observed from Figure 3 that the optimum cutting parameters for main cutting force were: a1 (0.1 mm), f1 (0.05 mm/rev) and V3 (200 m/min). Figure 4 also displayed that, the optimum cutting parameters for surface roughness were obtained as a1 (0.1 mm), f1 (0.05 mm/rev) and V2 (150 m/min).

Table 4. Experimental results based on L_9 orthogonal array and their S/N ratios

Exp. no	Depth of cut (a)	Feed rate (f)	Cutting speed (V)	*Ra* (µ)	*S/N* (dB)	*Fc* (N)	*S/N* (dB)
1	0.1	0.05	100	0.139	17.1397	62.73	-35.9495
2	0.1	0.1	150	0.16	15.9176	84.01	-38.4866
3	0.1	0.15	200	0.212	13.4732	93.08	-39.3771
4	0.2	0.05	150	0.155	16.1933	79.88	-38.0488
5	0.2	0.1	200	0.198	14.0667	112.22	-41.0014
6	0.2	0.15	100	0.267	11.4697	157.24	-43.9313
7	0.3	0.05	200	0.263	11.6008	87.54	-38.8441
8	0.3	0.1	100	0.31	10.1727	166.78	-44.4429
9	0.3	0.15	150	0.36	8.8739	193.62	-45.7390

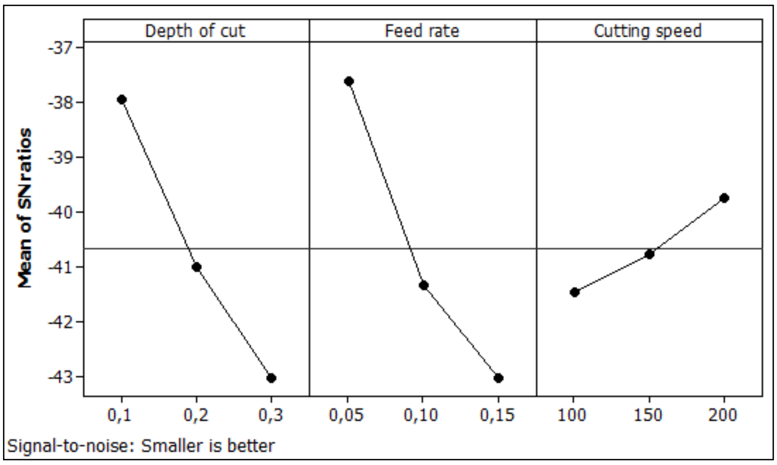

Figure 3. Main effect plot for S/N ratios of Fc

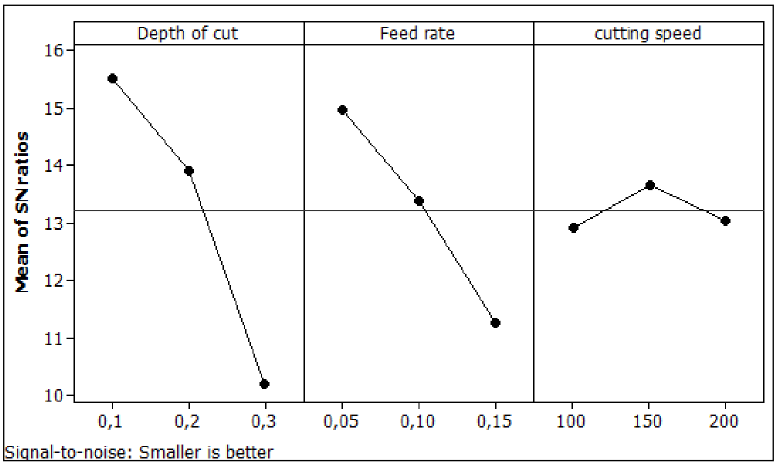

Figure 4. Main effect plot for S/N ratios of Ra

In the last stage of Taguchi method after the estimation of the optimum parameters, confirmation experiments are performed to display the accuracy of the optimization and to determine the improvement grade. Hence, the *S/N* ratio of performance characteristic for the experiments conducted at optimum parameters are calculated by using equation (2). Equation (1), which is the expression for performance characteristic, can be derived from by equation (3).

$$\eta_G = \bar{\eta}_G + (\bar{T}_O - \bar{\eta}_G) + (Vo - \bar{\eta}_G) + (fo - \bar{\eta}_G) \qquad (2)$$

$$Fc, Ra = 10^{-\eta_G/20} \qquad (3)$$

Here, η_G is the *S/N* ratio calculated at optimal level of factors (dB), $\bar{\eta}_G$ is the mean *S/N* ratio of all parameters (dB), $\bar{T}_O$, $\bar{V}_O$ and $\bar{f}_O$ are the mean S/N ratio once depth of cut, feed rate and cutting speed are at optimum levels, *Fc* and *Ra* are the calculated cutting force and surface roughness value, respectively. Consequently, comparison of predicted and experimental results for main cutting force and average surface roughness are given in Table 5 and Table 6, respectively.

Table 5. Results of confirmation experiments for main cutting force

	Initial cutting parameters	Optimal cutting parameters	
		Prediction	Experimental
Level	a2f1V2	a1f1V3	a1f1V3
Main cutting force, (N)	79.88	50.09	53.81
S/N ratio (dB)	-38.0488	-33.9965	-34.6172
Improvement of S/N ratio	3.4316 dB		
Prediction error (dB)	0.6207		

Table 6. Results of confirmation experiments for surface roughness

	Initial cutting	Optimal cutting parameters	
		Prediction	Experimental
Level	a2f1V2	a1f1V2	a1f1V2
Surface roughness, (µm)	0.155	0.122	0.132
S/N ratio (dB)	16.1933	17.7259	17.5885
Improvement of S/N ratio	1.3952 dB		
Prediction error (dB)	0.1374		

The confirmation experiments results showed that prediction error became 0.6207 dB for the main cutting force and 0.1374 dB for the average surface roughness. It has been confirmed that the cutting force and surface roughness can be reduced significantly with Taguchi optimization, as a result of the machinability research on hardened AISI H10A hot work tool steel with uncoated CBN cutting tools and minimum quantity lubrication (MQL) cutting environment. Considering the differences between the predicted results for the cutting force and the surface roughness with the results of confirmation experiments, it was concluded that a remarkable success has been achieved by Taguchi method.

4. CONCLUSIONS

In this study, machinability experiments on hardened AISI H10A hot work tool steel with uncoated CBN inserts were performed under minimum quantity lubrication (MQL) condition. The effects of cutting parameters (feed rate, depth of cut and cutting speed) on the *Fc* and *Ra* were analyzed according to Taguchi experimental design. Obtained results were summarized below

- It was determined that *Fc* and *Ra* increased with increasing depth of cut and feed rate in MQL cutting conditions and this situation was referred to increasing chip cross-section with increasing feed rate and depth of cut.
- In the optimization of the cutting parameters for the cutting force by the Taguchi method, cutting depth of 0.1 mm, feed rate of 0.05 mm/rev and cutting speed of 200 m/min were found to be optimum conditions.
- In the optimization performed for the surface roughness, cutting depth of 0.1 mm, feed rate of 0.05 mm/rev and cutting speed of 150 m/min were found to be optimum conditions.
- MQL application is strongly recommended in order to increase efficiency in hard turning processes on account of the above-mentioned evaluations.

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