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Modeling & Optimization of Surface Roughness & Vibration Amplitude in Heat Assisted End Milling of SKD 11 Tool Steel using Ball Nose Tool

A. K. M. Nurul Amin[1,a], Muhd Hafiz B. Md. Saad[1], and Muammer D. Arif[1,b]

[1]Dept. of Manufacturing and Materials Engineering, International Islamic University Malaysia (IIUM), Jalan Gombak, 53100 Kuala Lumpur, Malaysia.

[a]email: akamin@iium.edu.my, [b]email: marif@mtu.edu

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Abstract. Tool steel - SKD 11 is frequently used in industries for making dies and molds. This grade is chosen for its toughness, strength, and hardness maintained up to high temperature. However, the same properties make the steel extremely difficult and expensive to machine using conventional approaches. Heat assisted machining has been found wide spread application in recent years to improve machinability of difficult-to-cut materials. This research paper presents the outcome of an investigation on heat assisted end milling of SKD 11 conducted on a vertical machining center using ball nose coated carbide inserts. The Design of Experiments (DoE) was done using the Response Surface Methodology, in order to develop empirical mathematical models of surface roughness and vibration in terms of cutting speed, feed, axial depth of cut, and heating temperature. The models were checked for significance using Analysis of Variance (ANOVA). 3-D response surface graphs of the interactions of primary cutting parameters with the responses were plotted. Optimization was then performed by using the desirability function approach. From the graphs and optimized results it was concluded that the primary input parameters could be controlled in order to reduce vibration amplitude and produce semi-finished machined surfaces applying induction heat assisted technique.

Introduction

Machining of hard-to-cut materials like SKD 11 is an important stage in the production of many components such as blanking and cold-forming dies, which are essential in automotive industries. SKD11 (tool steel) is preferred for its excellent wear resistance and deep hardening properties. These hard-to-cut materials are extremely difficult and costly to machine by conventional methods due to their detrimental effects on tool life. Therefore, researchers have investigated methods to improve the machinability of these materials, whilst ensuring the preservation of their desired properties.

To reduce tool wear and surface roughness, the heat assisted machining technique has been investigated by various researchers. Trent et al. [1] stated that the basic requirement was that the work-piece's surface be preheated to just below its re-crystallization temperature. This would reduce the shear strength, thus making the machining easier and eliminating the problems of low cutting speeds, feeds, and heavy loads (on the machine bearings). Mahdavinejad [2] stated that power consumption during turning was primarily required in shearing and plastic deformation of the work-piece for metal removal purposes. Since, both shear strength and hardness of most materials decrease with increasing temperature, he postulated that an increase in the work-piece heating temperature would reduce the power consumed for machining as well as the stresses acting on the tool.

Mukherjee et al. [3] found that the cutting parameters in high speed milling could be controlled in order to reduce vibration, surface roughness, and tool wear. They carried out statistical evaluation of metal cutting parameters in hot machining and found that temperature, rather than cutting speed, had more dominant effect on reducing surface roughness. They claimed that preheating increased the ductility of the work material, which was conducive to chip formation and flow. Amin et al. [4] studied the benefits of heat assisted end milling of hardened D2 steel and found that peak chatter amplitude was reduced (by 75%), average tool nose wear was lower, and surface roughness was lesser, especially at higher cutting speeds. Amin et al. [5] investigated the influence of workpiece heating on chatter in end milling of carbon steel and observed that it lowered the chatter amplitude and increased the stock removal rate.

This research investigated the heat assisted high speed end milling of tool steel - SKD 11 using ball titanium nitride coated nose tool. Design of Experiment (*DOE*) approach in Response Surface Methodology (*RSM*) was employed in order to develop empirical mathematical models of surface roughness (R_a) and chatter amplitude (V) using cutting speed (V_c), axial depth of cut (*Doc*), feed rate (f), and heating temperature of the work-piece (T) as the input parameters. The responses were subsequently optimized using the desirability function (*DF*) approach.

Experimental Details

A CNC Vertical Machining Centre (VMC ZPS, Model: MCFV 1060) was used for the end milling operations (Fig. 1). A 16 mm diameter ball nose tool with circular coated carbide insert was employed as the tool for cutting an AISI D2 steel slab. An induction heating coil (capacity: 25 kVA) was used for preheating the work-piece (Fig. 2). The coil was mounted just ahead and in proximity of the cutting tool. This arrangement allowed enough time to substantially heat only the surface of the work-piece, prior to machining. The work-pieces surface temperature was measured using an infrared pyrometer (Omega OS-651, temperature range: -29 to 1093°C, accuracy: ±1%). The preheating system was calibrated so as to obtain a desired work-piece's surface temperature for a particular rated current value and a specific feed rate during machining. Vibration data was measured using a Kistler (50 g) accelerometer connected to the spindle. The data was collected using Dewtron signal analyzer and displayed using 'DASY Lab' software. The frequency range investigated was from 100 to 10,000 Hz. Mitutoyo surface profilometer (SJ-400) was used to measure R_a.

Fig. 1: VMC milling center

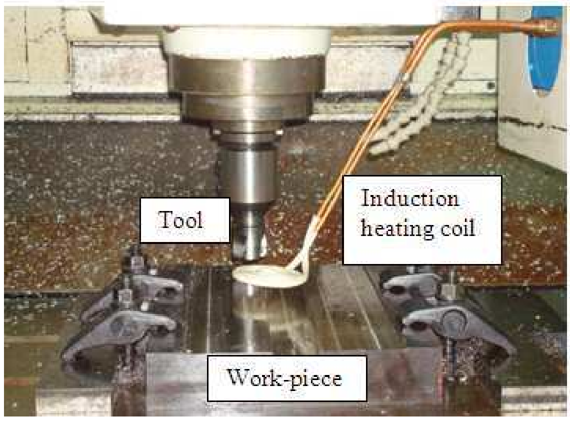

Fig. 2: Preheating setup

A Central Composite Design (*CCD*) model in *DOE* was used to determine the requisite number of experimental runs (17). The ranges of the four input parameters are listed in table 1 below. The radial depth of cut was kept constant at 4 mm for all experimental runs.

Table 1: Ranges of the input parameters

Sl. No.	Variable	Lower Limit	Upper Limit	Unit
1	Cutting Speed 'Vc'	50	100	m/min
2	Axial Depth of Cut 'Doc'	0.5	1.5	mm
3	Feed/Tooth 'f'	0.25	0.5	mm
4	Temperature 'T'	250	550	ºC

Results and Discussions

The experimental results for R_a and peak vibration amplitude are shown in Table 2. The results were then used to develop the empirical mathematical models for R_a and V (Eq. 1 & 2).

Table 2 : Experimental results for surface roughness and vibration

Run	Cutting speed, Vc (m/min)	Axial Doc (mm)	Feed/tooth, f, (mm)	Temp (ºC)	Ra (µm)	Vibration (Volts)
1	75	1	0.5	400	0.62	0.00719
2	100	0.5	0.25	550	0.39	0.03416
3	75	1	0.38	400	0.42	0.02044
4	50	0.5	0.25	250	0.63	0.00608
5	100	0.5	0.5	250	0.53	0.00653
6	50	1.5	0.5	550	1	0.00787
7	50	1	0.38	400	0.56	0.00929
8	100	1.5	0.25	550	0.38	0.00653
9	75	1	0.38	250	0.55	0.02486
10	100	1.5	0.5	250	0.9	0.0702
11	100	1	0.38	400	0.37	0.01452
12	50	1.5	0.25	250	0.64	0.00685
13	75	1	0.25	400	0.32	0.00719
14	50	0.5	0.5	550	1.2	0.00678
15	75	0.5	0.38	400	0.58	0.02117
16	75	1.5	0.38	400	0.59	0.01407
17	75	1	0.38	550	0.53	0.01249

$$R_a = 0.44 - 0.095\ V_c + 0.15\ f + 0.018\ Doc - 1.000E\text{-}002\ T + 0.016\ (V_c)^2 + 0.021\ f^2 + 0.14\ Doc^2 + 0.091\ T^2 - 0.044\ V_c\ f + 0.069\ V_c\ Doc - 0.049\ V_c\ T + 0.021\ f\ Doc + 0.064\ f\ T - 0.074\ Doc\ T. \quad (1)$$

$$V = 0.016 + 2.615E\text{-}003 V_c + 3.080E\text{-}003\ Doc - 6.185E\text{-}003\ T - 1.895E\text{-}003\ V_c\ f + 4.273E\text{-}003 V_c\ Doc - 4.720E\text{-}003\ V_c\ T + 0.011\ f\ Doc - 8.615E\text{-}003\ f\ T - 0.011\ Doc\ T. \quad (2)$$

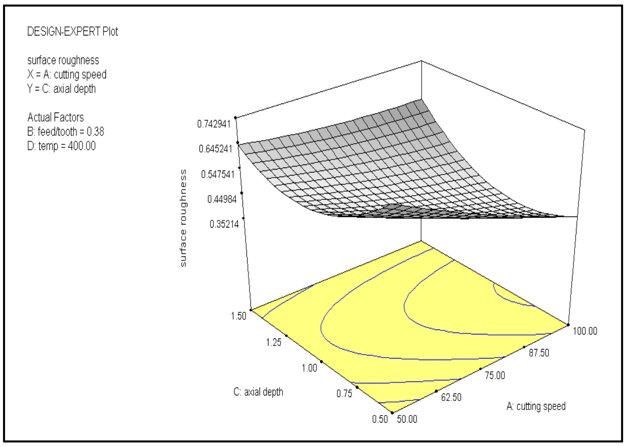

Fig. 3 : Response surface plot of surface roughness vs. cutting speed and axial depth of cut

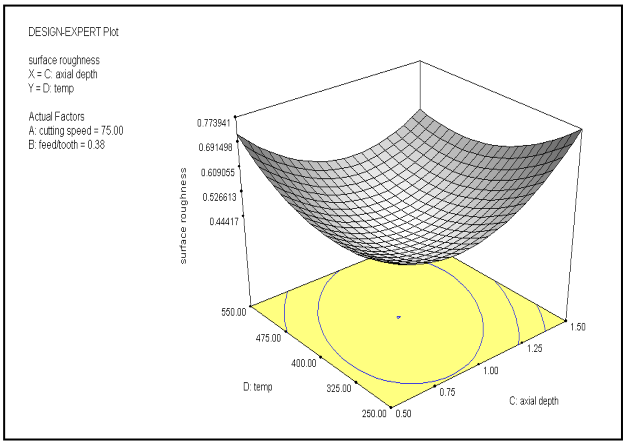

Fig. 4 : Response surface plot of surface roughness vs. temperature and axial depth of cut

The model above was verified to 95% confidence level using Anova. 3-D response surface plots (Fig. 3 & 4) were then developed in order to observe the interaction effects of two independent parameters on R_a while the remaining parameters were held at their middle level values. It was noticed that the interaction term V_c*Doc and Doc*T had significant effect on R_a. From fig. 3 it was inferred that maximum V_c and minimum Doc resulted in minimum possible R_a. Fig. 4 illustrated that the optimum temperature was around 400°C which is even more apparent in Fig. 5.

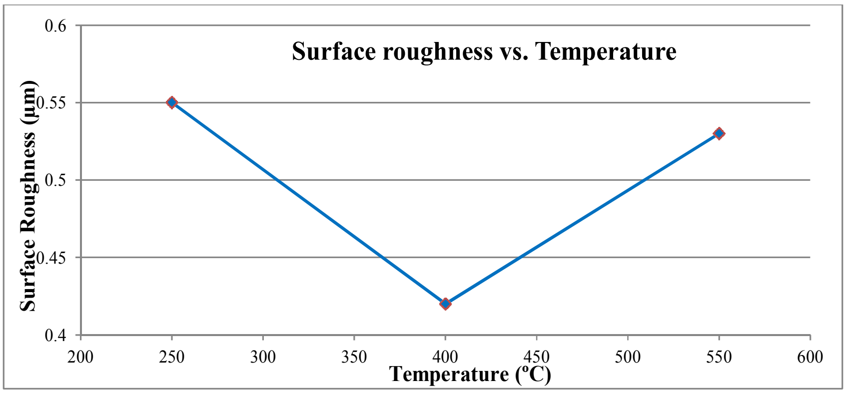

Fig. 5: Graph of surface roughness vs. temperature

The model equation above was verified to having greater than 95% confidence level using Anova. 3-D response surface plots (Fig. 6 & 7) were subsequently developed to determine the interaction effects. From fig. 6 it was noted that *V* was minimum at a temperature of aroung 400 ˚C. Fig. 7 demonstrated that *V* was smallest whenever one of the two interacting input parameters (*Doc or f*) was maximum while the other was minimum. Fig. 8 showed that the *V*decreased as the *T* was increased.

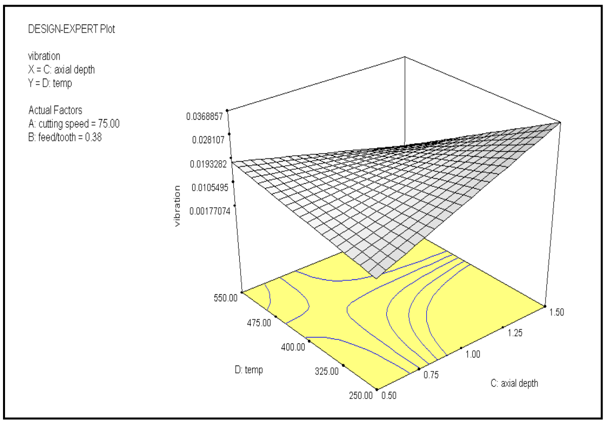

Fig. 6: Vibration 3-D Graph Model (combination between axial depth of cut and temperature)

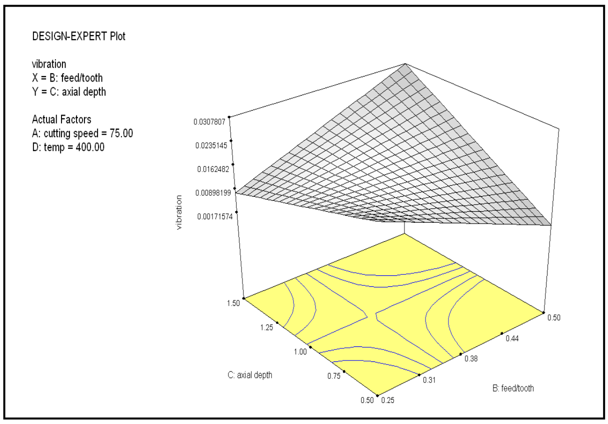

Fig. 7: Vibration 3-D Graph Model (combination between axial depth of cut and feed/tooth)

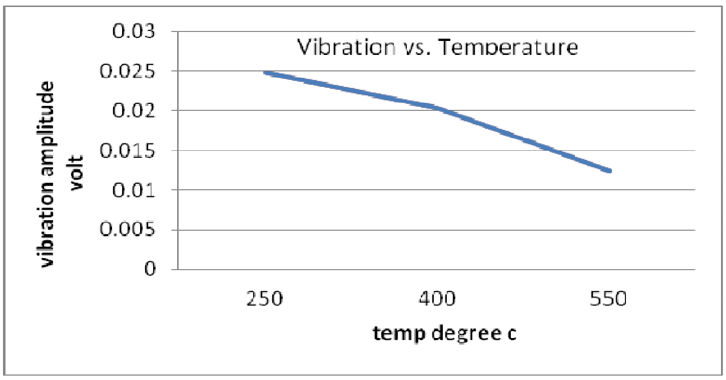

Fig. 8: Graph of vibration amplitude vs. temperature

Optimization. The DF approach predicted three optimum solutions for R_a (table 3). The first solution with the smallest R_a value of 0.314848 micrometers was selected.

Table 3: Optimization results for surface roughness

Solutions

Number	cutting speed	feed/tooth	axial depth	temp	surface roughi	Desirability
1	74.39	0.25	1.23	469.53	0.314848	1.000
2	70.79	0.25	1.14	437.27	0.319831	1.000
3	92.19	0.25	1.36	533.41	0.319766	1.000

In the case of vibration amplitude optimization (Table 4), *DF* also suggested 3 optimal solutions. However, the first solution with vibration amplitude value of 0.00607989 volts was selected as it had the highest desirability (0.997).

Table 4: Optimization results for vibration amplitude

Number	cutting speed	feed/tooth	axial depth	temp	vibration	surface roughi	Desirability	
1	90.25	0.25	1.36	550.00	0.00607989	0.325879	0.997	Selected
2	89.29	0.25	1.36	550.00	0.00594753	0.326524	0.996	
3	98.59	0.25	1.39	550.00	0.00617132	0.327714	0.995	

Conclusions

This research found that heat assisted end milling of SKD11 steel was conducive to obtaining lower surface roughness and vibration amplitude. Following are the particular conclusions drawn:

1 Temperature and cutting speed had the most significant effects on resultant surface roughness and generated peak vibration amplitudes. The preferred value of the work-piece surface temperature was between 400 and 500˚C as observed from the graphical plots and optimization results.
2 The minimum obtainable R_a was less than that obtained in semi finished operations (< 0.4 µm) thus eliminating the need for post machining grinding operations.

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