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Theoritical and Experimental Investigation In Prediction of Tool Life in Preheated Machining of AISI D2 Hardened Steel

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ABSTRACT: The tool life of TiAlN coated carbide tools was investigated at various combinations of cutting speed, feed and preheating temperature in end milling of AISI D2 hardened steel under room temperature and preheated machining conditions. Sufficient number of experiments was conducted based on the central composite design (CCD) which was adopted by response surface methodology (RSM) to generate tool life prediction values. The experimental results show that preheated machining led to appreciable increasing tool life compared to room temperature machining. The percentage of tool life increase was between 190-315 % depending on preheating temperature. Preheating of the work material with higher heating temperatures (250-450 ^{0}C) gives significant improvement in terms of tool life.

Keywords: *Hardened steels, Preheated machining, Tool life, Tool wear*

1. INTRODUCTION

Tool life prediction plays an important role in modern industry for sustainable manufacturing and product design. The productivity of a machining system and machining cost, as well as quality and integrity of the machined surface strongly depend on tool wear and tool life. Sudden failure of cutting tools leads to loss of productivity, rejection of parts and consequential economic losses [1].

The advent of several advanced difficult-to-cut materials such as the heat resistant tool steels has posed a great challenge in their machining. During the last few decades numerous studies have been conducted to improve the machinability of these materials and many large organizations have invested considerably in exploring and developing new techniques to minimize machining costs of these materials while maintaining their quality requirements. The benefits for the manufacture of components from hardened steel are substantial in terms of reduced machining costs and lead times, in comparison with the more traditional route which involves machining in the annealed state, heat treatment, grinding or electrical discharge machining (EDM), and manual finishing [2]. Recent advances in cutting tool and machine tool technologies have opened up new opportunities for investigation in machining hard materials and especially for bulk removal of material.

Preheating of workpiece by induction heating has been recently reported to enhance the machinability of materials. The latest work done by Amin et al [3] were carried out with induction heating in end milling of AISI D2 hardened steel using PCBN inserts. They observed that preheated machining of the material leads to surface roughness values well below 0.4 μm, such that the operations of grinding as well as polishing can be avoided at the higher cutting speeds. They added that preheated machining was able to reduce the amplitude of the lower frequency mode of chatter by almost 4.5 times at the cutting speed of 50 m/min. It was also established by several earlier studies [4-7] that preheating had great potential in lowering chatter. The primary causes of this stable cutting need to be studied in the perspective of material properties and damping capability of the material in the preheated condition. The primary objective of preheating is to enhance the ductility of the material for easier chip formation and better chip flow over the rake surface of the tool. In addition preheating is expected to improve the tool life and improve surface finish of the machined components. But preheating may lead to softening of the hardened workpiece. In the earlier study by Amin, et al [3], preheating temperature was in between 100-150 °C and this might not substantially change the hardness of the material. Hence, in the present study an attempt has been made to carry out an investigation in hot machining of end milling operation of AISI D2 hardened steel using induction heating. To discern differences in machinability, the test workpieces were machined with higher range of temperature from 250-450 °C.

2.0 EXPERIMENTAL DESIGN AND METHODOLOGY

The experimental set-up for hot machining of AISI D2 hardened steel is illustrated in Fig. 1. The milling operation is carried out on a VMC milling using a 40 diameter tool fitted with Sandvik 1030 PVD coated carbide inserts. End milling operation was performed under dry cutting conditions with a 5 mm constant radial depth of cut. In this experiment only one insert was used for each set of experimental conditions and moved every 100 mm pass of cut for flank wear measurement by Olympus Tool Maker microscope for which flank wear was recorded at 20 times magnification. An average 0.3 flank wear criteria was measured for each combination of cutting conditions in accordance with the ISO standard for tool life testing of end milling (ISO Standard 8688-2, 1989).

Induction heating machine of 25kVA capacity was used for preheating (online) heating of the workpiece with a heating coil mounted ahead in close proximity of the tool as shown in Fig. 1. The temperature on the surface of the work material was measured with the help of an infrared pyrometre. Workpiece preheating temperatures were measured during a dry run of the machine using the same feed rates as used during actual machining. Different current values were used under the varying feed rates to obtain the actual workpiece preheating temperature.

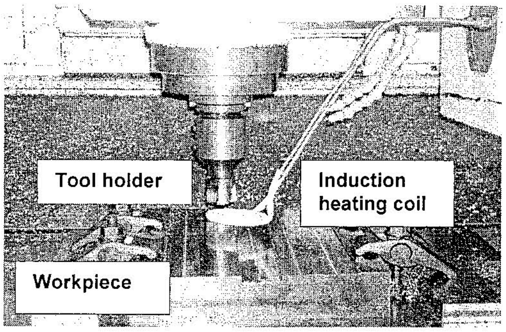

Figure 1: Experimental set-up of preheated machining

2.1 Workpiece Materials

The material used was AISI D2 hardened steel and was hardened by oil quenching and tempered to the hardness value in range of 56-62 HRC. The workpiece was prepared beforehand in the form of 300 mm x 250 mm x 100 mm.

2.2 Cutting Tool Materials

The end milling tool used was a Sandvik Coromill 390 Endmill: R390-020B20-11L employing one indexable insert code Sandvik 1030 Coromill 290 inserts R290-12T308E-PL. The TiAlN coated carbide inserts were used as received from the supplier using four sided edges. Fig. 2 and Table 1 show the schematic diagram of tool insert and its geometry respectively.

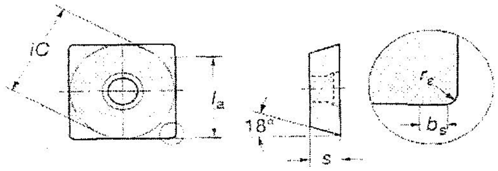

Figure 2: Schematic diagram tool insert geometry of PVD Coated Carbide (Sandvik 1030)

Table 1: Tool insert geometry of PVD Coated Carbide (Sandvik 1030)

Max. a_p	iC	l_a	S	b_s	r_ε
6	13.29	6.4	3.97	1.46	0.9-1.1

3. DESIGN METHODOLOGY USING RSM

The relationship between tool life and other independent variables is modelled as follows;

$$TL = CV^k \theta^l f^m \quad (1)$$

Where 'C' is a model constant and 'k', 'l' and 'm' are model parameters. The above function (1) can be represented in linear mathematical form as follows;

$$\mathrm{Ln}\,(TL) = \ln C + k \ln V + l \ln \theta + m \ln f \quad (2)$$

The first-order linear model of the above Eq. (2) can be represented as follows;

$$\hat{y}_1 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \quad (3)$$

Where, $\hat{y}_1$ is the estimated response based on first-order equation and y is the measured tool life on a logarithmic scale, $x_0 = 1$ (dummy variable), x_1, x_2, x_3 are logarithmic transformations of cutting speed, preheating temperature and feed respectively. The parameters b_0, b_1, b_2, and b_3 are to be estimated where ε the experimental error. The second-order model can be extended from the first-order equation as follows;

$$\hat{y}_2 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \quad (4)$$

Where, $\hat{y}_2$ is the estimated response based on the second-order model. Analysis of variance (ANOVA) is used to verify and validate the model.

The cutting conditions were selected by considering the recommendations of the cutting tool's manufacturer (Sandvik Tools) and the knowledge of practices, gathered through contemporary literatures on hard machining. The three main selected parameters: cutting speed, preheating temperature and feed were then coded to the levels using the following transformations;

$$X_1 = \frac{\ln V - \ln 56.57}{\ln 72.28 - \ln 56.57}; X_2 = \frac{\ln \theta - \ln 335}{\ln 413 - \ln 335}; X_3 = \frac{\ln f - \ln 0.044}{\ln 0.079 - \ln 0.044} \quad (5)$$

The independent variables with their corresponding selected levels of variation and coding identification are presented in Table 2. A well-planned design of experiment can substantially reduce the number of experiments and for this reason a small CCD with five levels was selected to develop the first order and second order models. This is the most popular class of designs used for fitting these models and has been established as a very efficient design for fitting the second order model [8]. The analysis of mathematical models was carried out using Design Expert version 6.0 package for both the first and second order models. The machining process carried out in random manner in order to reduce error due to noise. The overall cutting conditions with CCD is presented in Table 3.

Table 2: Independent variables with levels and coding identification.

Indep. Variables	Levels in Coded Form				
	$-\sqrt{2}$	-1	0	+1	$+\sqrt{2}$
Cutting speed (V) (m/min) (X_1)	40	44.27	56.57	72.28	80
Preheating temp.(θ) (celcius) (X_2)	250	273	335	413	450
Feed (F) (mm/tooth) (X_3)	0.02	0.025	0.044	0.079	0.10

Table 3: Design cutting conditions with CCD.

Trial no. (T)	Location in CCD	Actual Form		
		Cutting speed (m/min) (X_1)	Preheating temp. (celcius) (X_2)	feed (mm/tooth) (X_3)
1	Factorial	72.28	413	0.025
2	Factorial	72.28	273	0.079
3	Factorial	44.27	413	0.079
4	Factorial	44.27	273	0.025
5	Center	56.57	335	0.044
6	Center	56.57	335	0.044
7	Center	56.57	335	0.044
8	Center	56.57	335	0.044
9	Center	56.57	335	0.044
10	Axial	40.00	335	0.044
11	Axial	80.00	335	0.044
12	Axial	56.57	250	0.044
13	Axial	56.57	450	0.044
14	Axial	56.57	335	0.020
15	Axial	56.57	335	0.100

4. RESULTS AND DISCUSSION

4.1 Development of First & Second Order Models

Using the experimental results as obtained in the form of tool life values against all the set experimental conditions and followed by ANOVA analogy, the following tool life prediction model has been developed;

$$\ln(TL) = 4.07 - 0.57 x_1 + 0.18 x_2 - 0.45 x_3 \quad (6)$$

This is a first order model. By substituting Eq.(5) into Eq.(6), the model finally can be expressed as;

$$TL = 419\, V^{-2.33}\, \theta^{+0.86} f^{-0.77} \quad (7)$$

From this 1st order model (Eq.7) it is apparent that higher cutting speed will lower the tool life values followed by preheating temperature and feed. This equation is valid for cutting speed ($40 \leq V \leq 80$), preheating temperature ($250 \leq \theta \leq 450$) and feed ($0.02 \leq f \leq 0.1$). Since the second-order model is very flexible, easy to estimate the parameters with method of least square error, and work well in solving real response surface problems, the analysis was extended in prediction of more robust modeling of tool life. Using the experimental data the second order model is derived with the following equation;

$$\ln (TL) = 4.51 - 0.57x_1 + 0.13x_2 - 0.53x_3 - 0.32x_1^2 - 0.47x_3^2 - 0.16x_1x_2 - 0.095x_1x_3 \quad (8)$$

This model takes into account of the interaction and quadratic effects of the cutting variables. Both Eq. (7) and (8) representing 1st and 2nd order CCD models respectively have indicated that cutting speed would give significant effect on tool life values followed by preheating temperature and feed.

4.2 Tool Life Analysis

Tool wear is a great challenge in hardened steel machining, especially in milling. The experiments in this study show that tool wear in end milling of AISI D2 hardened steel is serious. This is maybe due to when the temperature was not high enough in their initial machining stage. In machining at room temperature, the tool wear is rapidly increased as the machining time was increased up to 35 min as shown in Fig. 3. In hot machining a uniform increase in tool wear was noticed as the machining time was increased. For both room and hot machining the tool life noticed were at 35 min (RT), 85 min (250 °C), 95 min (335 °C), 119 min (450 °C). These results indicate that as the temperature of machining increases, a corresponding increasing in the tool life was noticed due to the probably the reduction in the resistance to machining. Moreover a decrease in the strength of the workpiece through preheating on the top material surface layer produced a favourable condition for cutting. The decrease in the strength of the workpiece is induced by the influence of heat most of which is transferred to the chip-tool interface.

Increases in tool life were noticed when the heating temperatures were increased. In this study the longest tool lifes were noticed at 450 °C. However the AISI D2 hardened steel has a recrystallisation temperature range of 850 °F – 1050 °F (or 455 °C – 565 °C) as indicated in Fig. 4. Higher temperature used is detrimental to the workpiece microstructure where it might induce unwanted structural changes and consequently will increase tool wear. Therefore, in hot machining of AISI D2 hardened steel, the selection of 335 °C as the heating temperature might be appropriate in terms of the cost and workpiece considerations. It is shown in Fig. 5, tool life decreased as the feed rate was increased for both room temperature and preheated machining. These results also indicate that in preheated not much improvement of tool life was achieved at the highest feed rate of 0.1 mm/tooth. machining as the feed rate is increased, the tool life is further reduced. This phenomenon can be considered as the result of inefficient transfer of heat to the cutting zone during hot machining at high feed rates, because an adequate reduction in shearing stress of the workpiece was not achieved. Best effect of preheating is observed at the intermediate feed rate of 0.044 mm/tooth. It is also observed from the figure that the best effect of preheating is achieved at the intermediate cutting speed of 56.57 m/min. It is observed from Fig. 6 that the volume of metal that removed per tool life is higher in the case of preheated machining assuming the ISO standard value of average tool life of 0.3 mm. Fig. 7 shows the tool life improvement of hot machining of coated carbide when compared with room temperature where it shows tool life improvement in between 190 – 315 %. Best effect of preheating is attained at the temperature of 450 °C.

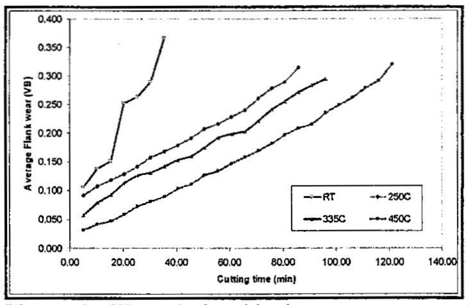

Figure 3: The relationship between average flank wear and cutting time at different cutting temperature [V=56.57 m/min, f=0.044 mm/tooth, d=1.0 mm]

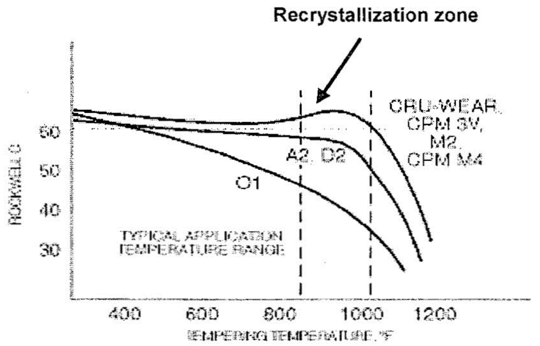

Figure 4: The relationship between hardness and tempering temperature for AISI D2

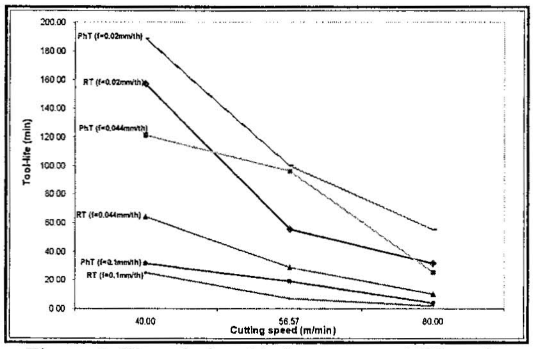

Figure 5: The relationship between tool life and cutting speed in different feed [RT and PhT]

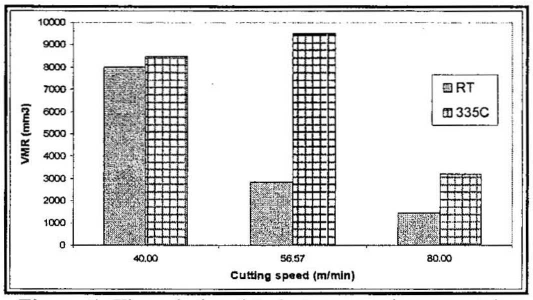

Figure 6: The relationship between volume metal removed and cutting speed for RT and PhT [f=0.044 mm/tooth, d=1.0 mm]

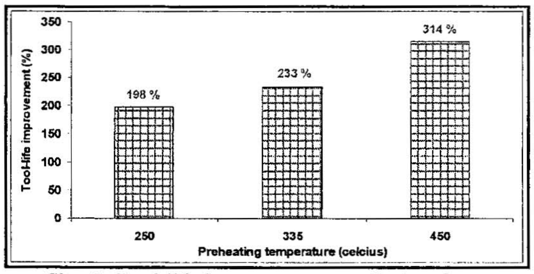

Fig. 7: Tool life improvement vs Preheating temperature [V=56.57 m/min, f=0.044 mm/th, d=1.0 mm]

4.3 Tool Wear Morphology

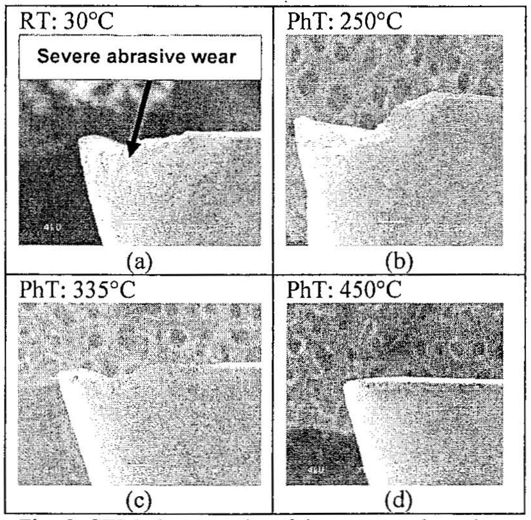

Fig. 8: SEM photographs of the worn tools at the end of machining tests: (a) at room-temperature, (b) at 250°C, (c) at 335°C, (d) at 450°C, [v=56.57 m/min, f=0.044 mm/tooth, d=1.00 mm].

The intensity of tool wear under conditions of room temperature machining comprised severe abrasive wear and attrition wear (Fig. 8a) that eventually led to extensive tool failure. These phenomena can be considered as the result of large carbides phases that have been found to be responsible for the enhanced abrasive wear resistance of D2 tool steel. During machining, these hard particles could be debris of the built-up edge or abrasive inclusions which include carbides, oxides and nitrides that could be present within the tools or workpiece. Abrasive wear is much likely to be a significant wear process with coated carbides due to the high hardness of tungsten carbide. According to Becze, et al [9], the carbide phase thus hampers the machinability of hardened D2 both in terms of increasing the flow stress of the material and inflicting severe abrasive wear on the tool. Fig. 8b of 250 °C preheated machining shows similar trend where the abrasive wear was also high. This was due to the insufficient supply of heat to induce appreciable softening of the work material. However, in 335 °C and 450 °C preheated machining (Figs. 8c and 8d) the occurance of uniform average wear on the cutting edges were observed. Fig. 8d of 450 °C preheated machining presents the smooth type of wear, which features the characteristics of diffusion wear process. Many researchers agreed that the rate of diffusion wear is temperature dependent. Diffusion wear is a mechanism where a constituent of a workpiece material diffuses into or forms a solid solution with the tool or chip material. In most of the cases, the work material was found to form a layer, similar to built-up-edge (BUE) on the tool surface (Figs. 8c,d). An EDAX analysis was performed to investigate this phenomenon. The analysis found that the significant existence of ferum (60.88 %Fe), carbon (25.3 %C) and chromium (4.9 %Cr) on the tool surface.

5.0 CONCLUSION

The following specific conclusions have been drawn from the work:

i) It has been possible to develop the first order (linear model) as well as the second order (quadratic model) for tool life. These models are valid within the ranges of the cutting parameters in end milling which for cutting speed range is 40 - 80 m/min, for depth of cut range is 0.5 - 2.0 mm and for feed range is 0.05 - 0.1 mm/tooth. Both models linear (1^{st} order) and CCD quadratic (2^{nd} order) have shown similar trend indicating that the cutting speed has the most significant influence on tool life followed by preheating temperature and feed.

ii) Preheating of the work material is found to much improvement in terms of maximum tool life. This improvement is achieved with the application of the higher heating temperatures (250-450 ^{0}C).

iii) Maximum improvement of tool life in preheated machining is achieved at intermediate feed value of 0.044 mm/tooth and cutting speed value of 56. 57 m/min.

iv) Abrasive wear, attrition wear and diffusion wear are found to be a very prominent mechanism of tool wear.

v) Worn land appears to be more severely deformed in the case of room temperature machining compared to that under preheated machining.

6. 0 ACKNOWLEDGEMENT

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7.0 REFERENCES

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