

Preheating in End Milling of AISI D2 Hardened Steel with Coated Carbide Inserts

M.A. Lajis^{1,a}, A.K.M. Nurul Amin^{2,b}, A.N. Mustafizul Karim^{2,c}, A.M.K. Hafiz^{2,d}

¹Faculty of Manufacturing and Industrial Engineering, UTHM, Malaysia

²Department of Manufacturing and Material Engineering, IIUM, Malaysia

^aamri@uthm.edu.my, ^bakamin@iiu.edu.my, ^cmustafizul@iiu.edu.my, ^dhafiz_fcc@yahoo.com

Keywords: Preheated machining, Hardened steels, Tool wear and Surface roughness

Abstract. This study was conducted to investigate the effect of preheating through inductive heating mechanism in end milling of AISI D2 hardened steel (60-62 HRC) by using coated carbide tool inserts. Apart from preheating, two other machining parameters such as cutting speed and feed were varied while the depth of cut constant was kept constant. Tool wear phenomenon and machined surface finish were found to be significantly affected by preheating temperature and other two variables. End milling operation was performed on a Vertical Machining Centre (VMC). Preheating of the work material to a higher temperature range resulted in a noticeable reduction in tool wear rate leading to a longer tool life. In addition, improved surface finish was obtained with surface roughness values lower than 0.4 μm , leaving a possibility of skipping the grinding and polishing operations for certain applications.

Introduction

With the advent of several advanced difficult-to-cut materials, and with the availability of heat resistant tool materials has posed a great challenge in industries. Hardened steel is one of these difficult-to-cut materials. 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 to the more traditional route which involves machining in the annealed state, heat treatment, grinding or electrical discharge machining (EDM), and manual finishing [1]. 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. For these reasons the growing interest for hot machining process is being developed in industry. In this method work-piece is softened by heating and thereby shear strength is reduced [2].

The technology of preheating or hot machining is not new and heat sources such as flame, electrical resistance, induction and plasma arcs were used [3]. Difficult-to-cut materials such as stainless steel, S-816 alloy, X-alloy, Inconel-X, Timken 16-25-6 and Navy Grade V, nickel chromium steel and alloy steels have been hot machined by Tour and Fletcher [4], Armstrong et al. [5], Krabacher and Merchant [6], Schmidt and Roubik [7] and Barrow [8]. Through analyses of their works, an important phenomenon is revealed - tool life increases to a maximum value for an optimum temperature range followed by a diminishing effect. Another important observation is the reduction in strain-hardenableity and flow stress of material with increase in preheating temperature. In recent times, hot machining for cutting hard materials has been adopted by several researchers. Dumitrescu et al. [3] applied High-Power Diode Laser (HPDL) in turning of AISI D2 tool steel. HPDL was found to inhibit saw tooth chip formation, suppress chatter, deter catastrophic tool fracture and bring about substantial reduction in tool wear and cutting forces leaving minimal effect on the integrity of the machined surface. It is, therefore, less likely to experience very adverse effects on the machined surface due to preheating.

Maity and Swain [2] adopted plasma assisted heating in turning of high manganese steel using carbide tool and concluded that the effect of increased workpiece temperature would have a very significant effect on tool life. Ozler et al. [9] integrated plasma gas heating in turning of austenitic manganese steel and noticed that tool life would increase with increase in heating temperatures. He concluded that 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.

Preheating of workpiece by induction heating has been recently reported to enhance the machinability of other materials. Amin et al [10] carried out preheated induction heating in end milling of AISI D2 hardened steel using PCBN inserts and observed that machining of preheated material led to surface roughness values well below 0.4 μm , with which grinding and polishing operations could be avoided for certain applications. Preheated machining has been found 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 other earlier studies [11-14] that preheating had great potential in lowering chatter.

It is apparent that preheating enhances the ductility of the material for easier chip formation and flow over the rake surface of the tool. This easier formation and flow of chip is expected to improve the tool life and surface finish of the machined components. Earlier study conducted by Amin, et al. [10] was restricted with a lower range of preheating temperature (100 to 150 $^{\circ}\text{C}$) to avoid a situation where preheating might lead to softening of the hardened work-piece. The current study was initiated to investigate the scope of preheating the work material to a higher level of temperature closer to re-crystallization temperature. Thus for AISI D2 hardened steel work material preheating was performed to a temperature range from 250 to 450 $^{\circ}\text{C}$ by using induction heating approach prior to end milling operation.

Experimental Set Up and Procedure

The machining operation was carried out on a Vertical Machining Center (VMC) using a 40 mm diameter tool holder fitted with Sandvik 1030 PVD coated carbide inserts. End milling operation was performed under dry cutting condition with a 5 mm constant radial depth of cut. Experimental set-up for hot machining of AISI D2 hardened steel is illustrated in Fig. 1. Down milling method was employed to secure the advantageous outcomes such as better surface finish, less heat generation, longer tool life, better geometrical accuracy and compressive stresses favorable for carbide edges as stated by Li et al. [15]. One edge out of the four cutting edges of a tool insert was used for each set of experimental conditions. Thus machining was initiated with a new sharp edge of an insert and continued for a 100 mm pass of cut followed by checking of the flank wear. This procedure was continued until the flank wear of the tool reached a magnitude of 0.30 mm. Olympus Tool Maker microscope was used to measure the flank wear with a magnification of (20x) twenty. The 0.30mm flank wear criterion was adopted in accordance with the ISO standard (ISO Standard 8688-2, 1989 for tool life testing of end milling).

Selection of Machining Conditions. The cutting conditions were selected primarily by considering the recommendations made by cutting tool manufacturer (Sandvik Tools) and the knowledge on practices gathered through contemporary literatures on hard machining. Selected three main parameters: cutting speed, feed and preheating temperature were changed while the axial depth of cut, d was kept constant at 1 mm. The ranges of parameters used for experimentation were: feed, f : 0.02 – 0.044 mm/tooth; cutting speed, V : 40 – 80 m/min; and preheating temperature, θ : 30 - 450 $^{\circ}\text{C}$. Re-crystallization temperature of work-piece material (AISI D2) [16] as depicted in Fig. 2 was taken into consideration to limit the maximum level of preheating temperature.

Experimental conditions were set by choosing the discrete values lying within the above mentioned ranges of the three selected parameters. Table 1 presents 20 sets of experimental conditions corresponding to which the machining operations were conducted. Data on tool life and surface roughness values of the machined surface are also included.

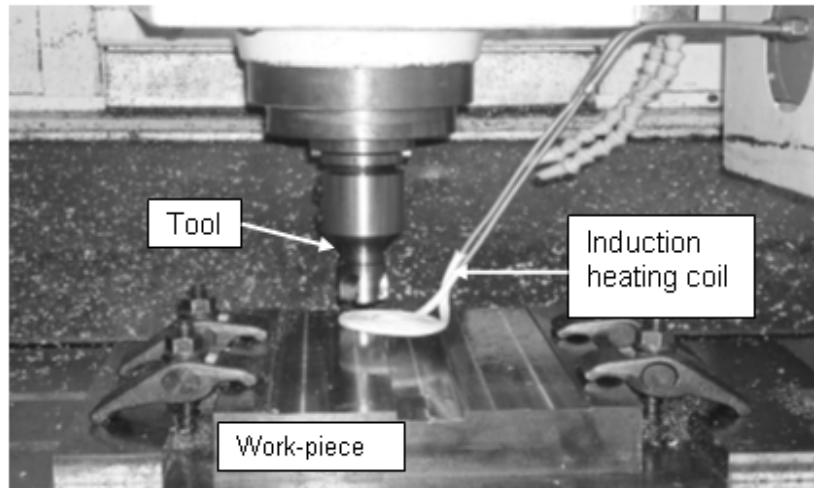


Figure 1: Experimental set-up of preheated machining

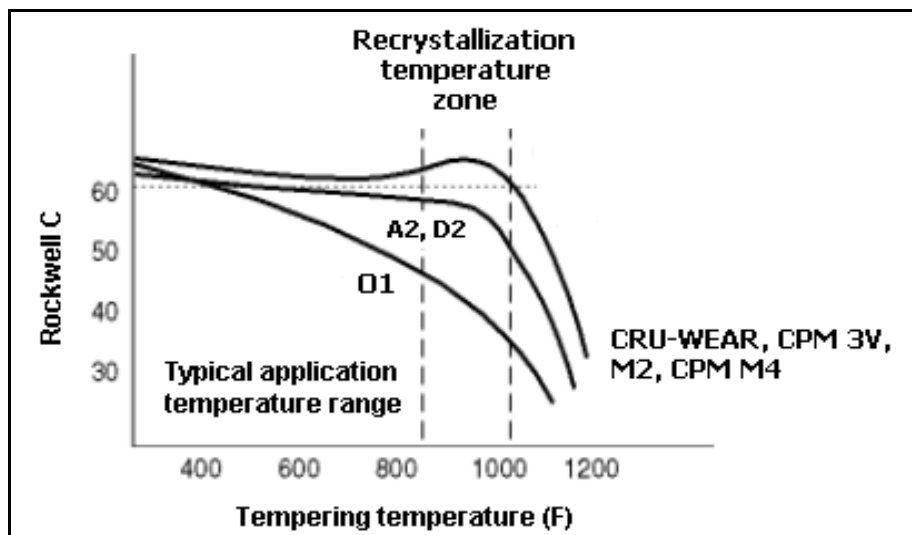


Figure 2: Hardness of D2 material among others as varied with tempering temperature

Process of Preheating. An induction heating device having a capacity of 25 kVA was used for preheating the work-piece. As shown in Fig.1 the induction heating coil was mounted just ahead and in close proximity of the cutting tool. This close position of the heating coil with the tool is expected not to allow enough time to transfer the heat substantially from the surface of the work-piece prior to machining. The temperature on the surface of the work material was measured with the help of an infrared pyrometer (Omega, OS-651 having the ability to measure temperature ranging between -29°C to 1093°C with an accuracy of $\pm 1\%$). Work-piece preheating temperature was calibrated by measuring for a particular current value and feed rate of the machine table as used during actual machining. So to obtain a desired preheating temperature of work-piece surface during machining operation a particular rated current value was set for a specific feed rate of VMC system.

Work and Cutting Tool Materials. The work material as received from supplier was in the form of a block hardened by oil quenching and tempered to a hardness range of 56-62 HRC having 300 x 250 x 100 mm in dimension. Hardness of work material was verified and found to comply with the supplier's specifications as presented in Table 2.

Table 1. Experimental condition with corresponding tool life and surface roughness

Experiment number	Cutting speed v (m/min)	Feed f (mm/tooth)	Preheating temperature θ ($^{\circ}\text{C}$)	Tool life TL (minute)	Surface roughness R_a (μm)
1	40.00	0.020	30	157.13	0.35
2	40.00	0.020	336	188.55	0.23
3	40.00	0.044	30	64.28	0.43
4	40.00	0.044	336	121.41	0.27
5	40.00	0.100	30	25.14	0.47
6	40.00	0.100	336	31.43	0.30
7	56.57	0.020	30	55.55	0.31
8	56.57	0.020	336	99.99	0.20
9	56.57	0.044	30	28.79	0.40
10	56.57	0.044	336	95.95	0.25
11	56.57	0.100	30	7.33	0.49
12	56.57	0.100	336	18.82	0.27
13	80.00	0.020	30	31.43	0.23
14	80.00	0.020	336	54.99	0.11
15	80.00	0.044	30	10.36	0.37
16	80.00	0.044	336	25.35	0.22
17	80.00	0.100	30	1.73	0.75
18	80.00	0.100	336	3.93	0.41
19	56.57	0.044	250	85.86	0.34
20	56.57	0.044	450	119.43	0.19

Table 2: Chemical composition and hardness of AISI D2

Chemical composition of the work material							Hardness (HRC)	
C	Si	Mn	Cr	Mo	V	P		S
1.50-1.60	0.10-0.40	0.15-0.45	11.0-12.0	0.60-0.80	0.9-1.1	0.03	0.03	56 - 62

As mentioned earlier the material used for machining operation was AISI D2, the microstructure (1000x magnification) of which is presented in Fig. 3.

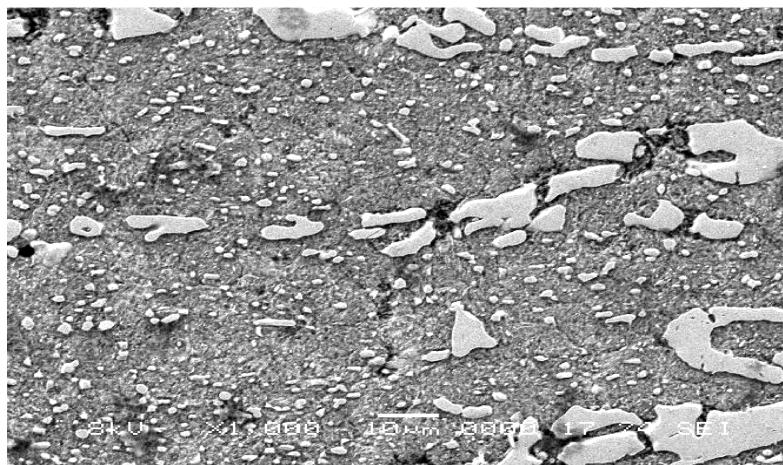


Figure 3: Microstructure of the AISI D2 after heat treatment

The end milling tool holder was a Sandvik Coromill 390 Endmill: R390-020B20-11L employing indexable inserts having code: Sandvik 1030 Coromill 290 R290-12T308E-PL. The TiAlN coated carbide inserts having four sided cutting edges were used as received from the

supplier. Fig. 4 presents a schematic diagram indicating the geometry of tool insert (Sandvik 1030) as coated through PVD method by manufacturer with relevant dimensions in Table 3.

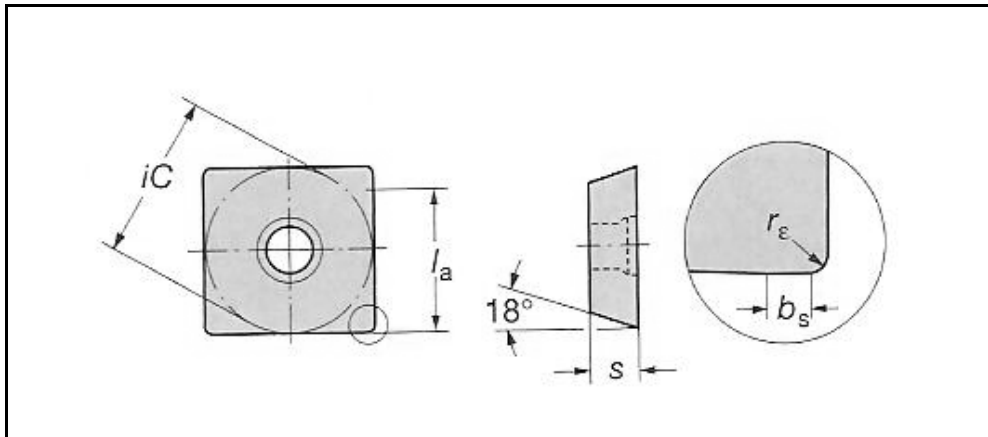


Figure 4: Geometry of TiAlN Coated Carbide tool insert (Sandvik 1030)

Table 3: Dimensions of tool insert (Sandvik 1030)

Maximum depth of cut, d (mm)	Dimensions are in mm				
	iC	l_a	S	b_s	r_ϵ
6	13.29	6.4	3.97	1.46	0.9-1.1

Experimental Results and Analysis

Maintaining tool wear to a minimum level is a great challenge in machining of hardened steel. Experiments in this study have demonstrated that tool wear in end milling of AISI D2 hardened steel without preheating could be quite severe and catastrophic. As shown in Fig. 5, the flank wear exceeded the limiting value of 0.3 mm in less than 7.33 minutes of machining time after cutting a length of 330 mm with a cutting speed of 56.57 m/min, feed of 0.1 mm/tooth, and depth of cut of 1.0 mm. In this case the tip of cutting tool insert ended up with breakage.

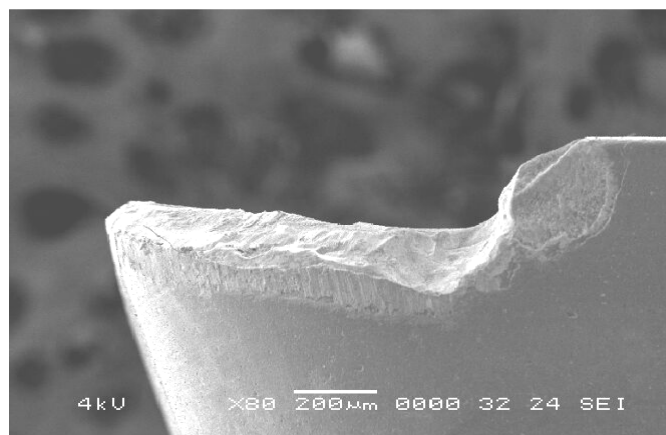


Figure 5: Tool wear observed after machining without preheating with cutting length of 300 mm [$V = 56.57$ m/min, $f = 0.1$ mm/th, $d = 1.00$ mm]

Tool Life Analysis. Progression of tool wear as a function of machining time with different preheating temperatures is presented in Figure 6. Enhanced tool life was obtained with the increase in preheating temperature. The longest tool life was achieved at 450 °C preheating

temperature. As indicated in Fig. 2, AISI D2 hardened steel re-crystallizes at a temperature ranging from 850 °F to 1050 °F which is equivalent to 455 °C – 565 °C. This is why the maximum preheating temperature applied in this experiment was set at 450 °C which is lower than the re-crystallization temperature. A preheating temperature higher than 450 °C could pose an undesirable effect on the work material especially in the context of hardness.

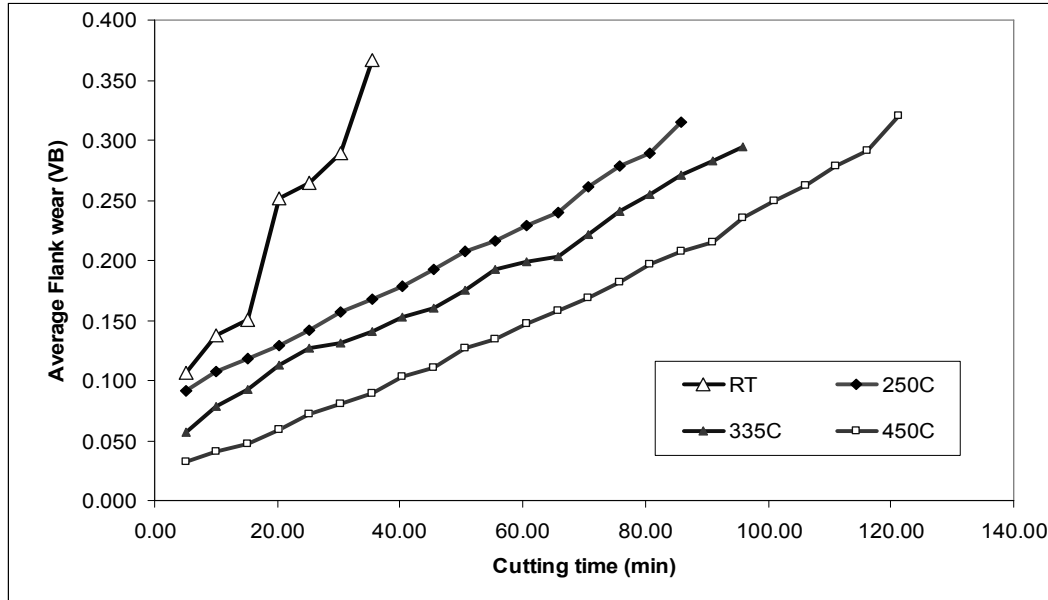


Figure 6: Influence of work-piece preheating temperature on flank wear with different cutting time [$V = 56.57$ m/min, $f = 0.044$ mm/tooth, $d = 1.0$ mm]

Tool life was estimated from the plot in Fig 6 for different preheated temperature and the values are 28.79, 85.86, 95.95, and 119.43 minutes respectively for preheating temperature of 30 °C (room temperature), 250 °C, 336 °C, and 450 °C. With these data a simple linear regression has been performed to correlate the tool life (TL, min) as a function of work-piece preheating temperature (θ °C). The developed linear of Eq. 1 exhibits a positive trend which is as follows:

$$T = 25.22 + 0.215 \theta \quad (1)$$

The positive coefficient of θ indicates that with the increase in preheating temperature the tool life increases. The coefficient of correlation (r) was found to be 0.992 leading to a coefficient of determination (r^2) of 0.99. The significance of r^2 value of 0.998 is that 99% of the tool life variation can be explained by the regression equation. However, this relationship should be valid under the preheating temperature range of 30 - 450 °C and other machining conditions used in conducting the experiments.

Fig. 7 illustrates six curves indicating the tool wear which correspond to the three cutting speeds (40, 56.57 and 80 m/min) and two temperatures (room temperature, 30 °C and a preheating temperature of 336 °C). It is clearly evident that tool life is enhanced with preheating for the same cutting speed. But the influence of preheating temperature on tool life is found to be high at cutting speed of 56.57 m/min and it becomes less prominent with the highest cutting speed (80 m/min).

As shown in Fig. 8, the higher the feed the lower is the tool life. These results may be explained in terms of higher stress encountered by the tool due to higher feed. However, the metal removed per tool life would be an appropriate criterion for assessing machinability.

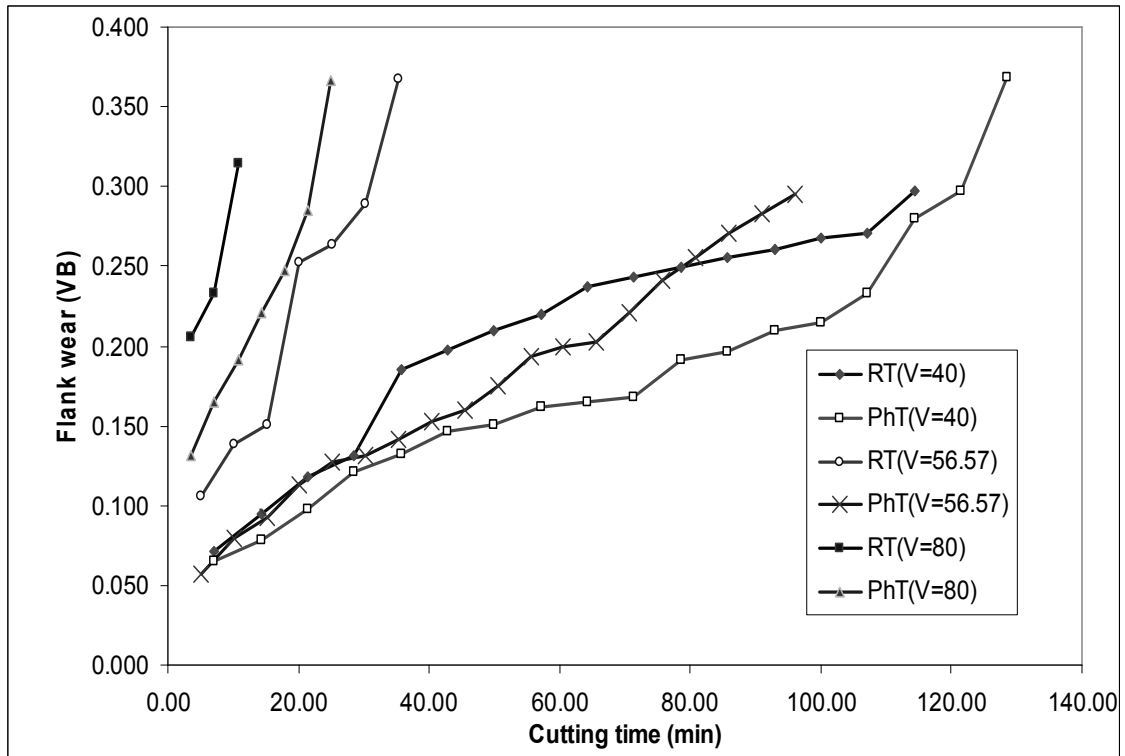


Figure 7: Flank wear influenced by preheating temperature and cutting speed with different cutting time [f=0.044 mm/tooth, d=1.0 mm]

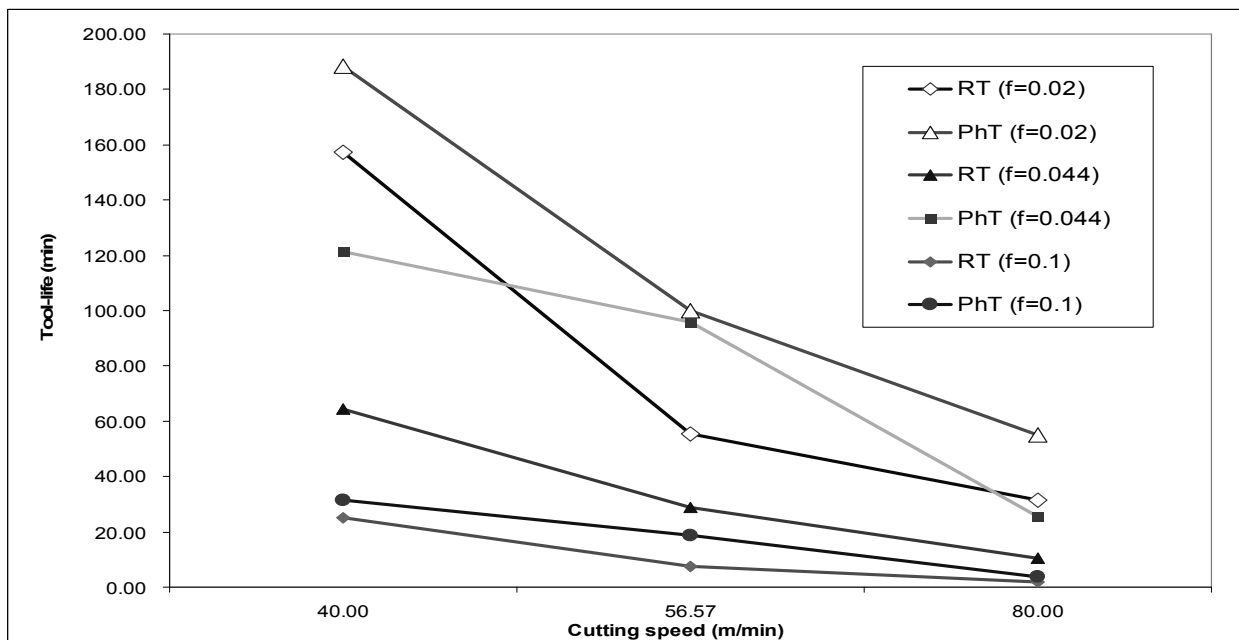


Figure 8: Tool life affected by feed at different cutting speeds and preheating temperature

Fig. 9 reveals the volume of metal removed (VMR) per tool life for different cutting conditions. In this case the feed was kept constant with 0.044 mm/tooth. Preheating temperature was 335 °C and cutting speed was varied into three levels. It is apparent that compared to room temperature, preheating led to higher VMR per tool life irrespective of any cutting speed.

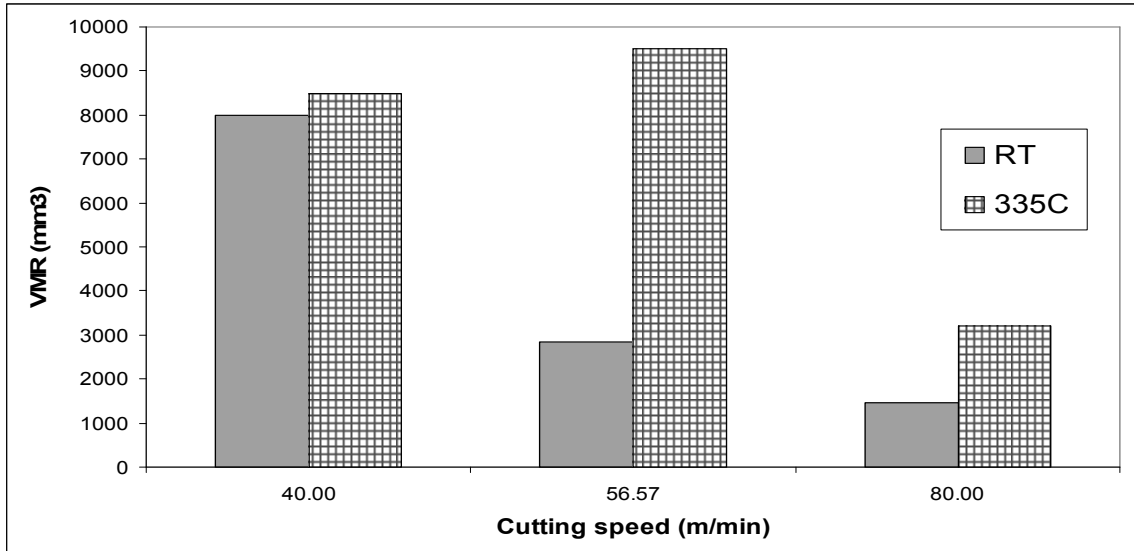


Figure 9: Volume of material removed per tool life influenced by preheating temperature and cutting speed. [$f=0.044$ mm/tooth, $d=1.0$ mm]

However, at lower cutting speed VMR increase due to preheating is marginal while at medium speed (56.57 m/min) it is maximum with a decline at the higher cutting speed.

Tool Wear Morphology. Tool wear followed by machining under room temperature was very intense with severe abrasive and notch wear of the cutting edge as evident in Fig. 10(a). These phenomena can be considered as the result of carbides constituents (as shown in Fig. 3) responsible for the enhanced abrasive wear resistance of D2 tool steel.

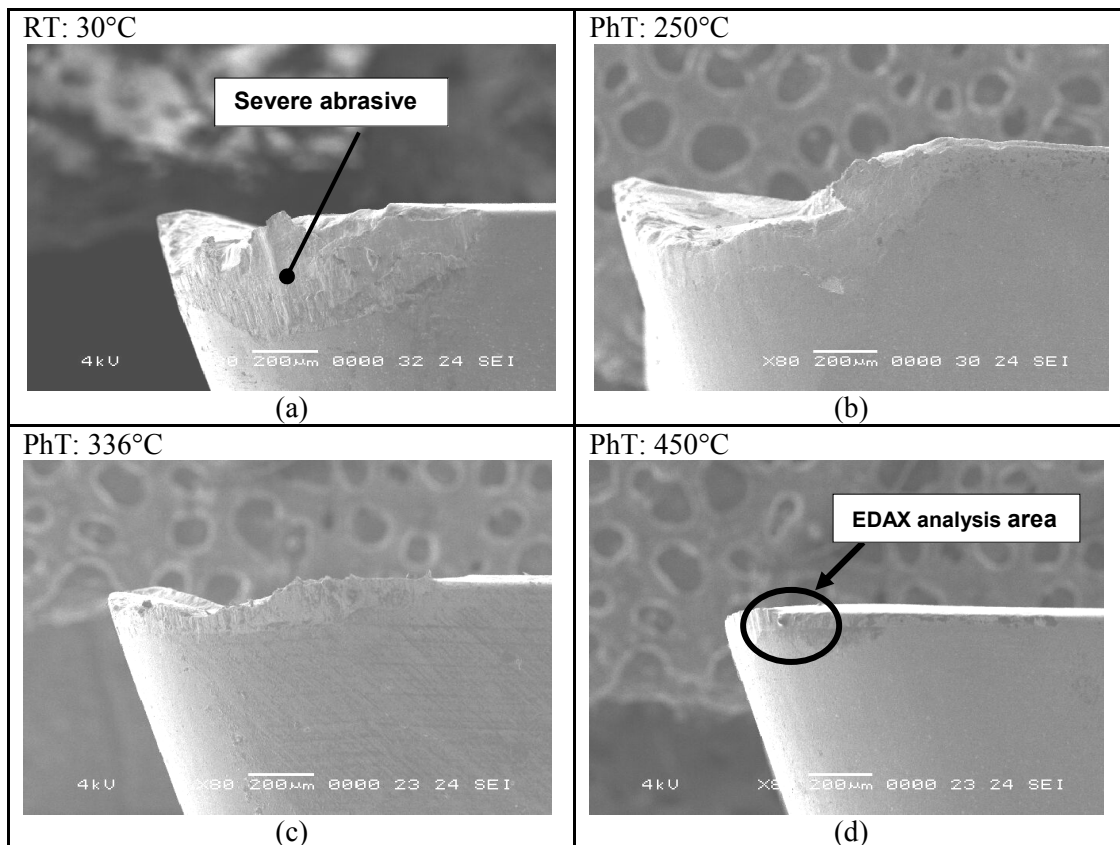


Fig. 10: SEM photographs of the worn tools at the end of machining tests: (a) at room-temperature, (b) at 250°C, (c) at 335°C, (d) at 450°C, [$v=56.57$ m/min, $f=0.044$ mm/tooth, $d=1.00$ mm].

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 [17], 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. 10(b) of 250 °C preheated machining shows slightly similar trend where the abrasive wear was not so severe compared to room temperature machining but there is a higher scale of notch wear. This may be due to the insufficient temperature to induce appreciable softening of the work material. Preheating of work material at 336 °C and 450 °C led to occurrence of uniform average wear on the cutting edges as shown in Fig. 10(c) and 10(d)). However, preheated machining with 450 °C presents a smooth type of wear with features characterizing the diffusion wear process which 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. Hence, an EDAX analysis, presented in Fig. 11, was performed to investigate the diffusion characteristics of the workpiece into the cutting tool. The analysis shows the significant existence of Ferum (60.88 %Fe), carbon (25.3 %C) and chromium (4.9 %Cr) on the tool surface as indicated in Fig. 11(b).

Machined Surface Roughness. Average of two surface roughness values, Ra values of the machined surface under different cutting conditions are plotted in Fig. 12. Irrespective of whether machining was performed at room temperature or with preheating, for a constant cutting speed surface roughness value increased with increasing feed. But with increase in cutting speed there is no such trend.

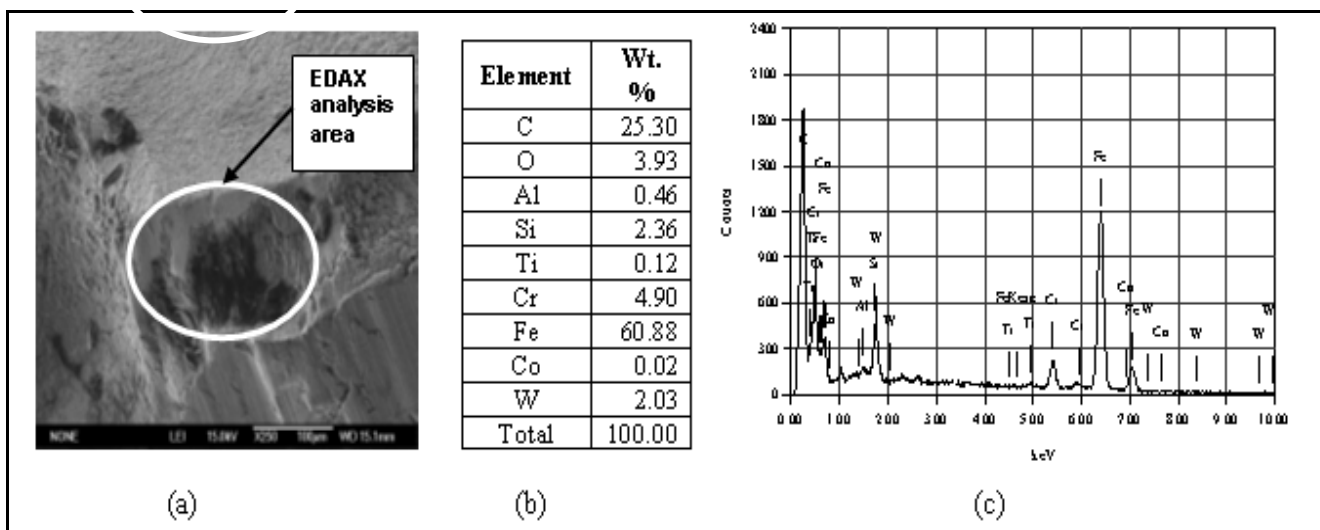


Figure 11: SEM and EDAX analysis of coated carbide for 450 °C PhT machining [v=56.57 m/min, f=0.044 mm/tooth, d=1.00 mm].

At lower level of feed (0.02 and 0.044 mm/tooth) surface finish had improved having lower roughness values as the cutting speed was increased. But at higher feed (f = 1.0 mm/tooth) surface finish had generally deteriorated having higher roughness values as the cutting speed was increased. It is observed from the plot that with preheating of work material surface roughness values are close to or below 0.3 μm at any combination of cutting speed and feed. In case of the cutting speed of 56.57 m/min at which maximum VMR was secured, even a better surface finish is possible to be maintained with lower range of roughness values. Thus with preheating it would be possible to skip the grinding and even polishing operation in preparing die and mold for certain applications.

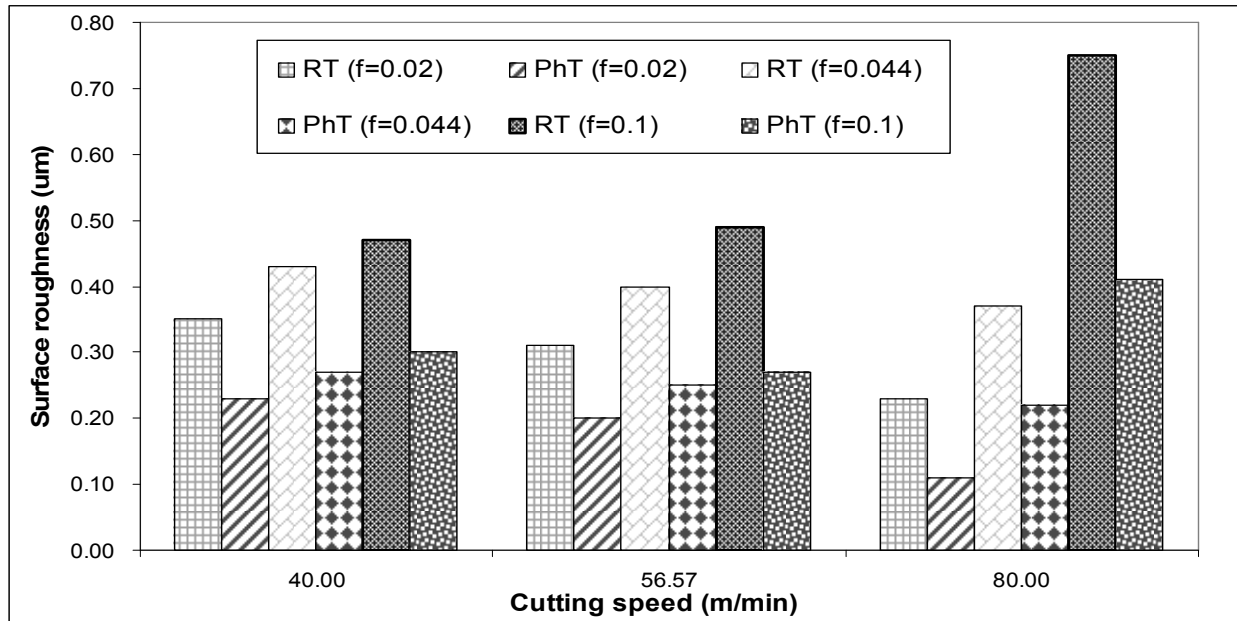


Fig.12: Machined surface roughness as influenced by cutting speed and preheating temperature [RT and PhT=335 °C]

Conclusion

Through the end milling of preheated AISI D2 hardened steel by using TiAlN coated carbide cutting tool it can be concluded that an overall enhanced machinability is achievable by preventing catastrophic damage of the cutting tool at higher levels of feed and cutting speed. To be specific the following conclusions can be drawn from the conducted experiments:

- i) Preheating of the AISI D2 work material enhances the tool life by slowing down the tool wear rate and preventing catastrophic tool failure.
- ii) Higher cutting speed was found to diminish the positive effect of preheating. A range of 40-60 m/min for cutting is expected to be suitable with a preheating temperature of 336 °C. Cutting speed of 56.57 m/min at which maximum VMR was secured, provides a better surface finish with roughness values lower than 0.3 µm.
- iii) Thus with preheating it would be possible to skip the grinding and even polishing operation in preparing dies and molds for certain applications.
- iv) A linear regression equation for tool life has been established for a range of preheating temperature (30 - 450 °C). This equation would be useful to predict the tool life for a particular preheating temperature lying within the range.
- v) However, incorporation of preheating mechanism obviously incurs costs, a detailed study is necessary to check whether the costs are offset by the benefits obtained through the process.

References

- [1] P. Koshy, R.C. Dewes, D.K. Aspinwall, High speed end milling of hardened AISI D2 tool steel (58 HRC), *Journal of Materials Processing Technology* 127 (2002), 266-273.
- [2] K.P. Maity, P.K. Swain, An experimental investigation of hot-machining to predict tool life, *Journal of Materials Processing Technology* (2007).
- [3] P. Dumitrescu, P. Koshy, J. Stenekes, M.A. Elbestawi, High-power diode laser assisted hard turning of AISI D2 tool steel, *Int. Journal of Machine Tools & Manufacture* (2006).
- [4] S. Tour, L.S. Fletcher, Hot spot machining, *Iron Age* (78), 164.
- [5] E.T. Armstrong, A.S. Closer, E.F. Kate, Machining of heated metals, *ASME* 35 (1951), 73.

-
- [6] E.J. Krabacher, M.E. Merchant, Basic factors in hot machining of metals, *Trans. ASME* 73 (1951), 761.
- [7] A.O. Schmidt, H.R. Roubik, Milling hot work piece, *Eng. Dig.* 10 (1949).
- [8] G. Barrow, Machining at high strength metals at elevated temperature using electrical current heating, *Annals of CIRP* 14 (1966), 145-151.
- [9] L. Ozler, A. Inan, C. Ozel, Theoretical and experimental determination of tool life in hot machining of austenitic manganese steel, *Int. Journal of Machine Tools & Manufacture* 41 (2006), 163-172.
- [10] A.K.M.N. Amin, S.B. Dolah, M.B. Mahmud, M.A. Lajis, Effects of workpiece preheating on surface roughness, chatter and tool performance during end milling of hardened steel D2, *Journal of Materials Processing Technology* 201 (2008), 466-470.
- [11] M.M. Abdelgadir, The effect of preheating of work material on chatter of VMC and machinability of work materials, *Masters Dissertation International Islamic University Malaysia* (2001).
- [12] A.K.M.N. Amin, M.M. Abdelgadir, The effect of preheating of work material on chatter during end milling of medium carbon steel performed on a vertical machining center (VMC), *ASME Journal of Manufacturing Science and Engineering* (2003), 674-680.
- [13] A.K.M.N. Amin, I. Abraham, N. Khairussima, Influence of preheating on the performance of circular carbide inserts in end milling of carbon steel, *Proceedings of the 3rd International Conference on Advanced Manufacturing Technology ICAMT, Kuala Lumpur* (2004).
- [14] Marlina Mahmud and Shuriani Dolah, Influence of preheating on chatter and machinability of hardened sSteel AISI D2 in end milling, *Undergraduate Thesis Kuliyyah of Engineering IIUM Kuala Lumpur* (2005).
- [15] H.Z. Li, H. Zeng, X.Q. Chen, An experimental study of tool wear and cutting force variation in the end milling of inconel 718 with coated carbide inserts, *Journal of Material Processing Technology* 180 (2006), 296-304.
- [16] Reed-Hill, Robert, Principles of Physical Metallurgy, *PWS Publishing*, 3rd edition, Boston (1994).
- [17] C.E. Becze, M.J. Worswick, M.A. Elbestawi, High strain rate shear evaluation and characterization of AISI D2 tool steel in its hardened state, *Machining Science and Technology* 5 (2001), 131-149.

Advances in Materials and Processing Technologies

10.4028/www.scientific.net/AMR.83-86

Preheating in End Milling of AISI D2 Hardened Steel with Coated Carbide Inserts

10.4028/www.scientific.net/AMR.83-86.56

DOI References

[1] P. Koshy, R.C. Dewes, D.K. Aspinwall, High speed end milling of hardened AISI D2 tool steel (58 HRC), *Journal of Materials Processing Technology* 127 (2002), 266-273.

doi:10.1016/S0924-0136(02)00155-3

[3] P. Dumitrescu, P. Koshy, J. Stenekes, M.A. Elbestawi, High-power diode laser assisted hard turning of AISI D2 tool steel, *Int. Journal of Machine Tools & Manufacture* (2006).

doi:10.1016/j.ijmachtools.2006.01.005

[9] L. Ozler, A. Inan, C. Ozel, Theoretical and experimental determination of tool life in hot machining of austenitic manganese steel, *Int. Journal of Machine Tools & Manufacture* 41 (2006), 163-172.

doi:10.1016/S0890-6955(00)00077-8

[10] A.K.M.N. Amin, S.B. Dolah, M.B. Mahmud, M.A. Lajis, Effects of workpiece preheating on surface roughness, chatter and tool performance during end milling of hardened steel D2, *Journal of Materials Processing Technology* 201 (2008), 466-470.

doi:10.1016/j.jmatprotec.2007.11.304

[12] A.K.M.N. Amin, M.M. Abdelgadir, The effect of preheating of work material on chatter during end milling of medium carbon steel performed on a vertical machining center (VMC), *ASME Journal of Manufacturing Science and Engineering* (2003), 674-680.

doi:10.1115/1.1596557

[15] H.Z. Li, H. Zeng, X.Q. Chen, An experimental study of tool wear and cutting force variation in the end milling of inconel 718 with coated carbide inserts, *Journal of Material Processing Technology* 180 (2006), 296-304.

doi:10.1016/j.jmatprotec.2006.07.009

[17] C.E. Becze, M.J. Worswick, M.A. Elbestawi, High strain rate shear evaluation and characterization of AISI D2 tool steel in its hardened state, *Machining Science and Technology* 5 (2001), 131-149.

doi:10.1081/MST-100103182