The Effect of Preheating of Work Material on Chatter During End Milling of Medium Carbon Steel Performed on a Vertical Machining Center (VMC)

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In the present work causes and after effects of chatter have been discussed and attempts have been made to control the occurrence of chatter during end milling operation conducted on a vertical machining center (VMC). Chatter has been treated as a resonance effect and preheating of the incoming work material layers using high frequency induction heating has been tried as a method of controlling chatter. It has been found that preheating results in substantial lowering down of acceleration amplitude of chatter in a wide range of cutting speed. This has facilitated low tool wear intensity, improved machined surface finish and low noise level during machining. Work material properties were practically unaffected due to low preheating temperature.

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1 Introduction

Modern manufacturing is characterized by high requirements on accuracy and productivity in a highly automated flexible manufacturing environment. Increased productivity has been achieved by employing high cutting velocities, feed rates and depths of cut. One of the restrictions limiting large material removal rates is the tendency of the machine tool to chatter. Trent, Talantov, Amin and others considered that the formation of chips with serrated teeth to be the primary cause of chatter [1–3]. Talantov and Amin have established that chatter arising during turning is a result of resonance, caused by mutual interaction of the vibrations due to serrated elements of the chip and the natural vibrations of the system components, e.g. the spindle and the tool holder [2–4]. It may be mentioned here that the frequencies of instability of the chip formation process are dependent of the work and tool materials and condition of cut. The magnitude of these frequencies may go up to 10,000 Hz and above. So the coincidence of these frequencies and the natural frequencies are possible. Such a coincidence results in resonance which is known as chatter. Chatter is undesirable because of its adverse effect on surface finish, machining accuracy, machine tool bearings, tool life [5] and operator's performance due to fatigue. Furthermore, chatter is also responsible for reducing output because, if no remedy can be found, metal removal rate has to be lowered until vibration-free performance is obtained [6]. Thus, for precision components made of advanced materials, it is extremely important to adequately control the machining process and ensure a stable operation with minimum vibrations.

Nachtigal et al. has proposed the use of an updated synthesis circuit for reduction of self-excited chatter vibrations of machine tools [7]. In this method the electrical signals corresponding to the fluctuation of the cutting force applied on the work piece and the tool are converted into displacement signals and compensatory actuators are made to provide forces to eliminate vibrational chatter. This method requires online condition monitoring for detecting chatter and taking remedial action, which may be difficult to implement in real life situation. Moreover, there are many excited frequencies during chatter and to simulate their effect in order to take remedial action may be not very practical. In another method, Delio [8] proposed to monitor the vibration signals during machining and automatically act on the spindle speed and the feed rate to bring the system to a stable state. This method may be suitable in the absence of active vibration control mechanisms and also it has its limitation of reducing production rate in order to control chatter.

Most of the control schemes applied to date for machining processes also lack long range predictive capabilities. This may critically hinder the effectiveness in a real-time implementation. In order to avoid the development of instabilities in a machining process, it is very important to identify and eliminate the causes of such instabilities in the process dynamics as well as the after effects of the resultant instabilities. To control the vibration of the machine tools and thus improve productivity and surface quality of the finished the plasticity of the work material through preheating of the latter. It was established by Amin earlier that the instability of chip formation could be lowered by preheating the work material during turning [9]. But the furnace heating method of the workpiece, employed in the investigation, is not quite suitable for application in real production situation for turning. Apart from this metal cutting process in end milling is distinguished from that of turning. The cutting process is intermittent and periodic vibrations at the tooth cutting frequencies are inherent in end milling, whereas the cutting process is continuous in turning. So it would be interesting to investigate the influence of job preheating on chatter during end milling using a more sophisticated and reliable experimental technique.

The present work aims at using high frequency induction heating as a method of preheating the work material layers approaching the cutting to improve vibration stability and machinability of the work material. To minimize heat losses during the heating process, only a small layer of work material was targeted for heating.

2 Experimental Setup and Procedure

Experiments were performed on Vertical Machining Center model: MLR 542. Figure 1 shows a Block Diagram of the Experimental Setup. It includes the preheating system and a data acqui-

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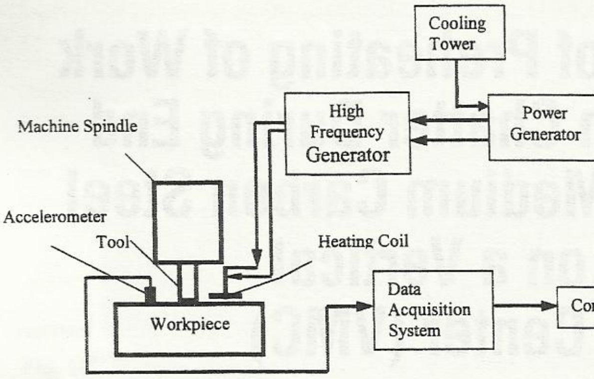
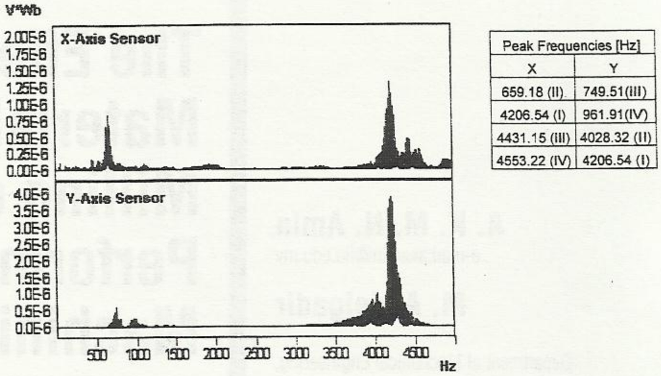


Fig. 1 Block diagram of the experimental setup



Peak Frequencies [Hz]	
X	Y
659.18 (II)	749.51(III)
4206.54 (I)	961.91(IV)
4431.15 (III)	4028.32 (II)
4553.22 (IV)	4206.54 (I)

Fig. 3 Natural frequency plots of the system detected by the *X* and *Y* axis sensors mounted on the spindle

sition system for recording the vibration frequency and amplitude. Software DASYLab 5 was used for analyzing the data. To preheat the workpiece, a Portable Transistor type Induction Heating Machine SP-25AB was used. The preheating coil was attached to the machine spindle with proper isolation. The coil was attached to the induction heater using a flexible coaxial cable. To study the tool wear mechanism photographs of the worn tool inserts were taken using a Scanning Electron Microscope (SEM) model JSM-T330. A Hiomet Measuring Microscope with an accuracy of 0.0001 mm was used to measure the tool flank wear. Mitutoyo Surface test model SJ-400 was used to measure the surface roughness of the machined surface. Plain carbon steel AISI 1040 was used as the work materials. Machining was performed with Sandvik end mill with a shank diameter of 32 mm fitted with two coated-carbide inserts of code R390-11 T3 04M-PM. The tool geometry and specifications are shown in Fig. 2. Experiments were performed both at room temperature (29°C) and with preheating of the workpiece. Speed, depth of cut and feed used for the experimental work were as follows: Speed: 100, 150, 200, 250 and 300 m/min, Depth of cut: 1 and 2 mm, Feed: 0.1 and 0.2 mm/tooth.

Preheating temperatures were found to vary depending on the feed rate. An experiment was carried out to determine the distribution of temperature in the workpiece during induction heating at various feed rates. Two capillary holes were drilled on the side of the workpiece at distances of 1 mm and 2 mm from the surface. Each hole was 12 mm deep. Thermocouples were inserted into the holes to measure the temperatures at these depths. Preheating was conducted with a dry run at table feeds corresponding to those applied during actual cutting. Workpiece surface temperatures were measured by an infrared thermometer.

Natural frequencies of the system with the 32 mm diameter end mill fitted in place were determined by striking the spindle with a mallet and recording the free vibration of the system using two sensors mounted along the *X* and *Y* directions on the spindle. The vibration plots are shown in Fig. 3. It may be observed from the plot that the prominent natural frequencies of the spindle system lie in the frequency range of 500–1000 Hz and 4000–4500 Hz. Frequencies of the prominent peaks are mentioned in the adjacent table. It has been also found by Israd [10] that the natural frequency of the chuck of the same machine is in the range of 600–700 Hz and that of the machine table is in the range of 350–500 Hz.

Vibration signals were recorded during cutting for all the cutting conditions as mentioned above. Results of four of these cutting conditions (as shown in Table 1) were thoroughly analyzed using the DASYLab 5 software. Surface roughness (R_a, R_y, R_z), was plotted using a Mitutoyo Surfacetest SJ-400. Tool wear measurements were conducted using standard procedures. Photographs of the inserts after machining at room temperature and with preheating were taken using a SEM.

3 Results and Discussion

3.1 Influence of Linear Feed on Preheating Temperature.

The results of the experiments conducted to determine the influence of feed on preheating temperatures are shown in Table 2. It may be observed from the table that an increase in feed rate leads to a reduction in the preheated temperature. This is observed because the temperature rise depends on the time that the workpiece is exposed to the induction frequency through the coil. Secondly, the temperatures at the surface and at 2 mm depth are almost equal, but are higher than those at 1 mm depth in all the cases.

3.2 Influence of Preheating on Peak Amplitudes of Chatter and Surface Roughness.

Vibration signals recorded during cutting were analyzed in the frequency range of 0–10,000 Hz in order to investigate the influence of preheating on peak values of acceleration amplitude of chatter which normally occurs at the natural frequencies of the system and at their immediate higher or lower harmonics. The acceleration amplitudes were recorded in the frequency domain for all the cutting conditions as mentioned earlier but detailed analysis of the influence of preheating on chatter amplitude and on surface roughness for two extreme cutting

l	iW	d_1	s	b_s	r_r	$\alpha_n{}^o$
11	6.8 mm	2.8 mm	3.59 mm	1.2 mm	0.8 mm	21deg

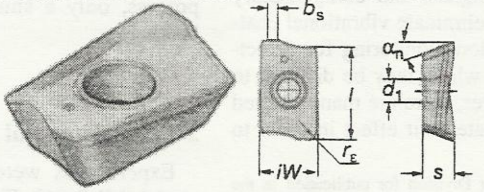


Fig. 2 Insert geometry

Table 1 Cutting conditions of the four cases taken up for detailed study

Cutting Speed m/sec	Feed (Z_t)=0.1 mm/tooth		Feed (Z_t)=0.2 mm/tooth	
	Depth of cut (D_c)=1 mm		Depth of cut (D_c)=2 mm	
	R. T.	Pr. H.	R. T.	Pr. H.
100	Case I		Case II	
300	Case III		Case IV	

R. T.=Room Temperature. Pr. H.=Preheated.

Table 2 Temperatures attained on the surface, 1 mm and 2 mm below the surface for various feed rates

Feed Rate mm/min	Temperature Attained, °C		
	On Surface	At 1 mm depth	At 2 mm depth
200	350	320	340
300	315	305	320
400	300	285	300
500	290	270	285
600	275	270	280
800	270	260	270
1000	265	255	265
1200	260	250	260

conditions, case I and case IV, as shown in Table 1, have been included in the paper. Figures 4–7 and Tables 3–6 show the results of these two cases.

3.2.1 *Case I (V_C=100 m/sec, D_C=1 mm and Z_t=0.1 mm/tooth).*

A. Influence of Preheating on Chatter. The recorded vibration signals in the frequency ranges from 1 to 1,000 Hz and 1,000 to 10,000 Hz for both normal cutting and cutting with preheating are shown in Fig. 4(a,b) and Fig. 5(a,b) respectively, and the results of a comparative study on the peak acceleration amplitudes at different sections of the frequency range are shown in Table 3. It may be observed from Fig. 4(a) that the vibration peaks appear in the frequency ranges of 400–600 Hz during machining at room temperature, which is close to the natural frequency range of 500–700 Hz of the system. It may be also observed from Fig. 4(b) that after preheating all the peaks except the ones in the 400–450 Hz range disappear. It may be noted from Table 3 that the peak amplitude values are reduced by 64% in this particular frequency range due to preheating of the work material. It may be further observed from Fig. 5(a) that the vibration peaks also appear during machining at room temperature in the frequency ranges of 3600–3800 Hz and 7200–8000 Hz, which are close to the natural frequency in the ranges of 4000–4300 Hz and its next higher harmonic (approximately twice the value). It is also observed from Fig. 5(b) that after preheating all the peaks disappear except two small peaks at the natural frequencies of the system. It may be also noted from Table 3 that the peak amplitude value is reduced by 90% to 95% in this particular frequency range due to preheating of the work material.

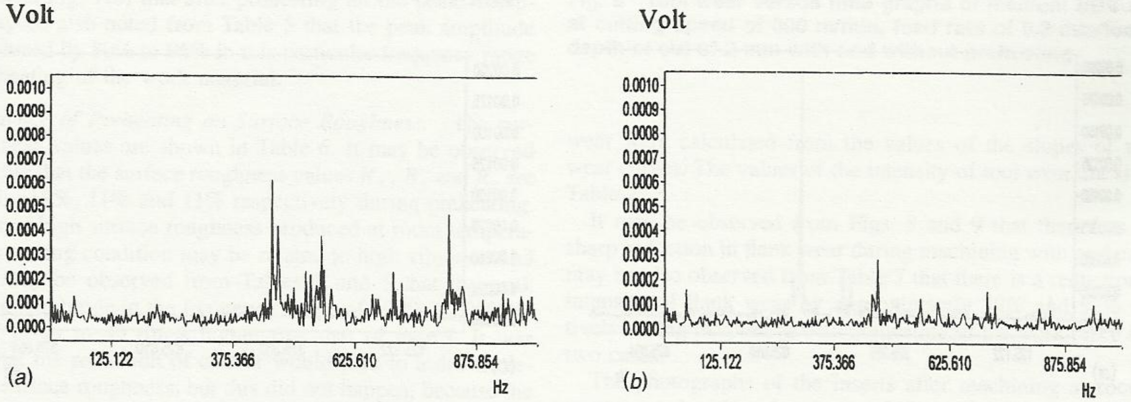


Fig. 4 Vibration acceleration amplitude versus frequency plots from 0 to 1000 Hz for depth of cut of 1 mm, feed rate of 0.1 mm/tooth and cutting speed of 100 m/min: *a*) at room temperature (29°C) and *b*) at 350°C of preheating

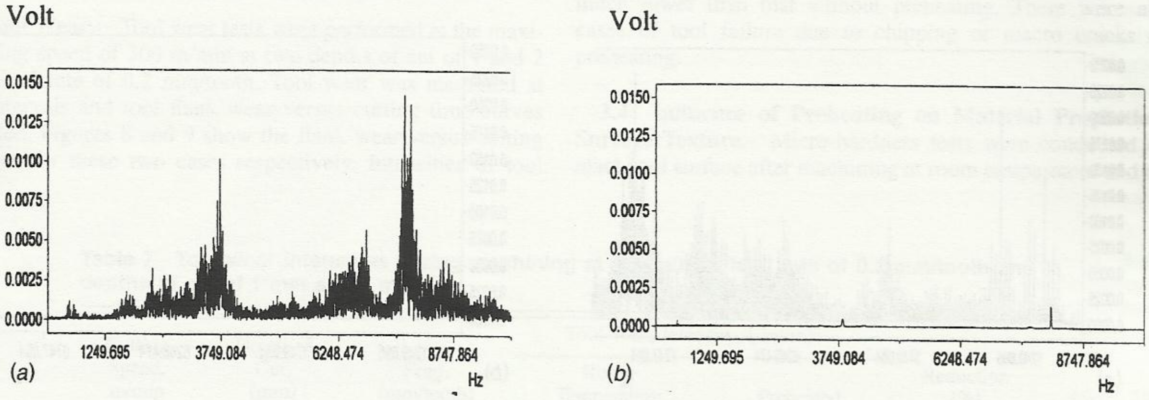


Fig. 5 Vibration acceleration amplitude versus frequency plots from 1,000 Hz to 10,000 Hz for depth of cut of 1 mm, feed rate of 0.1 mm/tooth and cutting speed of 100 m/min: *a*) at room temperature (29°C) and *b*) at 350°C of preheating

Table 3 Acceleration amplitudes of vibration and the percent reduction for case I (Cutting condition: cutting speed =100 m/min, depth of cut=1 mm and feed=0.1 mm per tooth)

Frequency range (Hz)	Max. Acceleration amplitudes (m/sec^2) Room Temperature (29°C)	Preheated at 350°C	Percent Reduction (%)
50–100	0.022555 (83.0 Hz)	0.00588 (80.0 Hz)	74
100–500	0.117680 (466 Hz)	0.04217 (437 Hz)	64
500–1000	0.098067 (566 Hz)	0.01079 (561 Hz)	89
1000–5000	1.010085 (3710 Hz)	0.05099 (3823 Hz)	95
5000–10000	1.412158 (7670 Hz)	0.13827 (8081 Hz)	90

B. Influence of Preheating on Surface Roughness. The surface roughness values are shown in Table 4. It may be observed from the table that the surface roughness values R_a, R_y and R_z are improved by 26%, 33% and 33% respectively during preheating. It may be also observed from the same table that the reduction in surface roughness due to preheating is not proportionate to the reduction of vibration amplitudes. It may be noted here that surface roughness depends among other factors on cutting speed, feed, depth of cut and work-tool material combination. So the reduction of vibration amplitude alone may not be able to substantially reduce the surface roughness, especially the feed marks of the tool will dictate the surface roughness. Another factor which may be responsible for relatively higher surface roughness will be explained in the subsequent section of this paper.

Table 4 R_a, R_y and R_z values for the two cutting conditions with and without preheating for case I

Property measured	At Room Temperature (29°C)	During Preheating at 350°C	Reduction of Roughness (%)
R_a (μm)	0.82	0.61	26
R_y (μm)	5.2	3.5	33
R_z (μm)	4.0	2.7	33

3.2.2 *Case IV (V_C=300 m/sec, D_C=2 mm and Z_t=0.2 mm/tooth)*

A. Influence of Preheating on Chatter. The recorded vibration signals in the frequency ranges from 1 to 1,000 Hz and 1,000 to 10,000 Hz for both normal cutting and cutting with preheating for case IV are shown in Fig. 6(a,b) and Fig. 7(a,b) respectively, and the peak acceleration amplitude values in this range are shown in Table 5. It may be observed from Fig. 6(a) that vibration peaks are observed in the frequency range of 400–600 Hz which are close to the natural frequency range of 500–1000 Hz of the system. It may be also observed from Fig. 6(b) that after preheating practically all the peaks disappear. It may be noted from Table 5 that the peak amplitude values are reduced by 78% to 98% in this particular frequency range due to preheating of the work material.

It may be further observed from Fig. 7(a) that the vibration peaks also appear during machining at room temperature in the

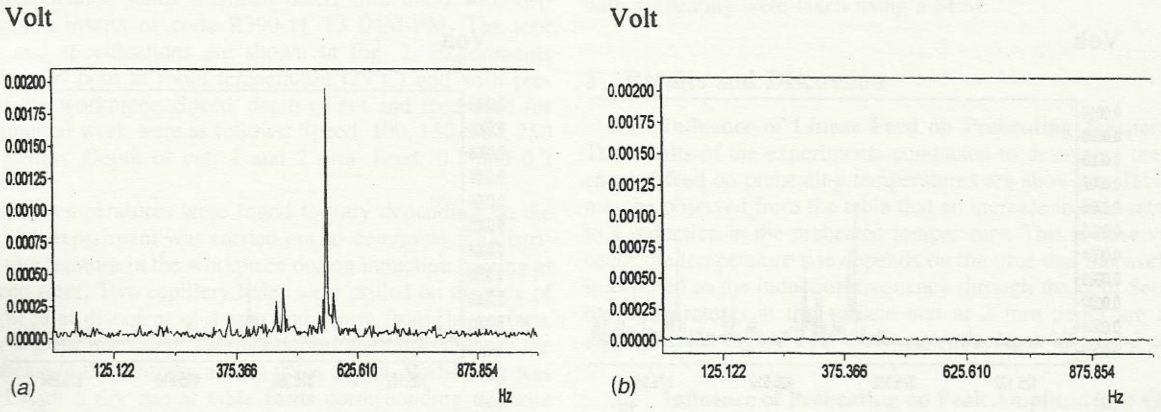


Fig. 6 Vibration acceleration amplitude versus frequency plots up to 1000 Hz for depth of cut of 2 mm, feed rate of 0.2 mm/tooth and cutting speed of 300 m/min: *a*) at room temperature (29°C) and *b*) at 260°C of preheating

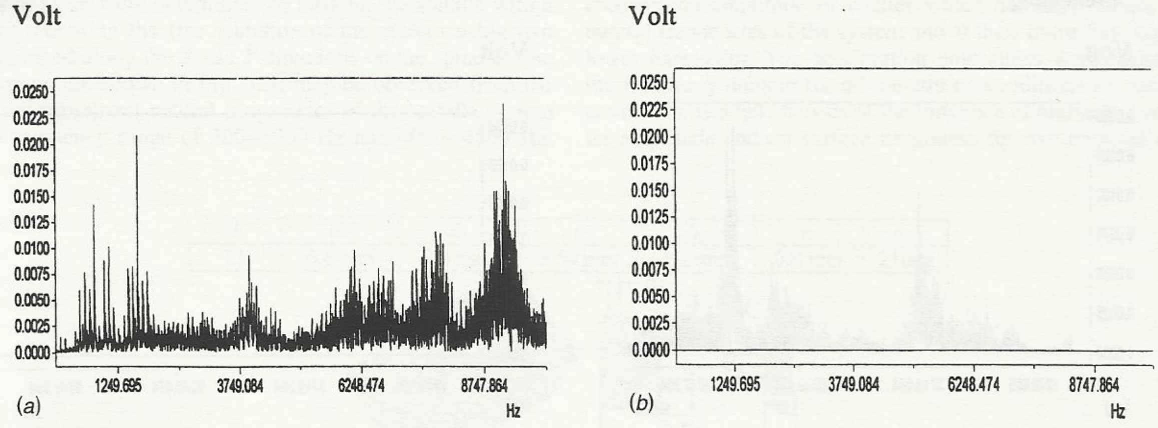


Fig. 7 Vibration acceleration amplitude versus frequency plots from 1,000 Hz to 10,000 Hz for depth of cut of 2 mm and feed rate of 0.2 mm/tooth and cutting speed of 300 m/min: *a*) at room temperature (29°C) and *b*) at 260°C of preheating

Table 5 Acceleration amplitudes of vibration and the percent reduction for case IV (Cutting condition: Cutting speed =300 m/min, depth of cut=2 mm and feed=0.2 mm per tooth)

Frequency range (Hz)	Max. Acceleration amplitudes (m/sec^2) Room Temperature (29°C)	Preheated at 260°C	Percent Reduction (%)
50–100	0.008826 (83.0 Hz)	0.00196 (80.0 Hz)	78
100–500	0.039227 (471 Hz)	0.00490 (456 Hz)	88
500–1000	0.192210 (561 Hz)	0.00294 (842 Hz)	98
1000–5000	0.022555 (3347 Hz)	0.00245 (2330 Hz)	89
5000–10000	0.046091 (9956 Hz)	0.00196 (7316 Hz)	96

Table 6 R_a, R_y and R_z values for the two cutting conditions with and without preheating for case IV (Cutting condition: Cutting speed=300 m/min, depth of cut=2 mm and feed=0.2 mm per tooth)

Property measured	At Room Temperature (29°C)	During Preheating at 260°C	Reduction of Roughness (%)
R_a (μm)	1.89	1.53	19
R_y (μm)	7.4	6.6	11
R_z (μm)	7.0	6.2	11

frequency ranges of 1100–1300 Hz, 3600–3800 Hz and 6000–9000 Hz, which are close to the natural frequency in the ranges of 4000–4300 Hz and its lower or higher harmonics. It may be also observed from Fig. 7(b) that after preheating all the peaks disappear. It may be also noted from Table 5 that the peak amplitude value is reduced by 89% to 96% in this particular frequency range due to preheating of the work material.

B. Influence of Preheating on Surface Roughness. The surface roughness values are shown in Table 6. It may be observed from the table that the surface roughness values R_a, R_y and R_z are improved by 19%, 11% and 11% respectively during preheating. The causes of high surface roughness produced at room temperature in this cutting condition may be related to high vibration and chatter. It may be observed from Tables 3 and 5 that the peak acceleration amplitude in the frequency range of 1000–10,000 Hz in case IV is up to 49 times higher that that of case I. It was expected that the reduction of chatter would lead to a drastic reduction of surface roughness, but this did not happen, because the increase in the displacement of the tool in case IV is much less than 49 times since displacement is $a \sin(\omega t)$ and the acceleration is $a\omega^2 \sin(\omega t)$. Nevertheless, the investigation of the machined surface is included in Sec. 3.4 of this paper.

3.3 Tool Wear. Tool wear tests were performed at the maximum cutting speed of 300 m/min at two depths of cut of 1 and 2 mm and feed rate of 0.2 mm/tooth. Tool wear was measured at definite intervals and tool flank wear versus cutting time curves were plotted. Figures 8 and 9 show the flank wear versus cutting time curves for these two cases respectively. Intensities of tool wear were calculated from the values of the slopes of the tool wear curves. The values of the intensity of tool wear are shown in Table 7.

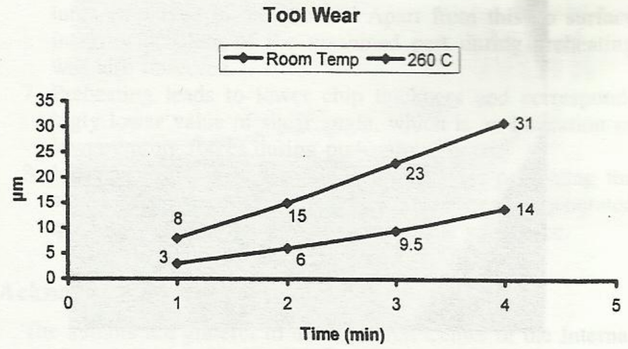


Fig. 8 Tool wear versus time graphs of medium carbon steel at cutting speed of 300 m/min, feed rate of 0.2 mm/tooth and depth of cut of 1 mm with and without preheating

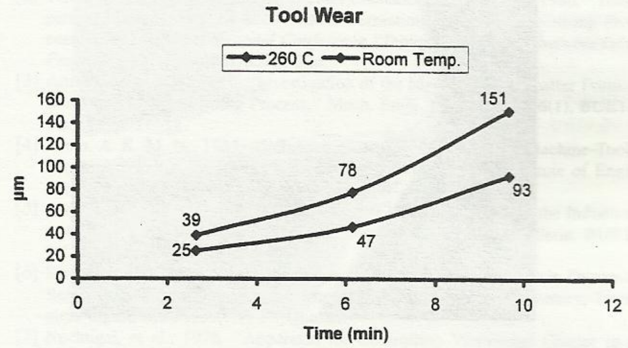


Fig. 9 Tool wear versus time graphs of medium carbon steel at cutting speed of 300 m/min, feed rate of 0.2 mm/tooth and depth of cut of 2 mm with and without preheating

It may be observed from Figs. 8 and 9 that there has been a sharp reduction in flank wear during machining with preheating. It may be also observed from Table 7 that there is a reduction in the intensity of flank wear by approximately 39% and 52% respectively during machining with preheating of the work piece in these two cases.

The photographs of the inserts after machining at room temperature and with preheating, at 300 m/min, feed rate of 0.2 mm/tooth and depth of cut of 2 mm, are shown in Figs. 10 and 11 respectively. It may be observed from these two figures that the wear is more uniform in the case of preheating with its magnitude much lower than that without preheating. There were also no cases of tool failure due to chipping or macro cracks during preheating.

3.4 Influence of Preheating on Material Properties and Surface Texture. Micro-hardness tests were conducted on the machined surface after machining at room temperature and on that

Table 7 Tool wear intensities during machining at 300 m/min, feed rate of 0.2 mm/tooth and depths of cut of 1 mm and 2 mm

Cutting Speed, m/min	Depth of Cut, (mm)	Feed, (mm/tooth)	Tool Wear Intensity, (μm/m) Room Temperature	Preheated	Reduction (%)
300	1	0.2	0.1067	0.0648	39.27
300	2	0.2	0.0256	0.0122	52.34

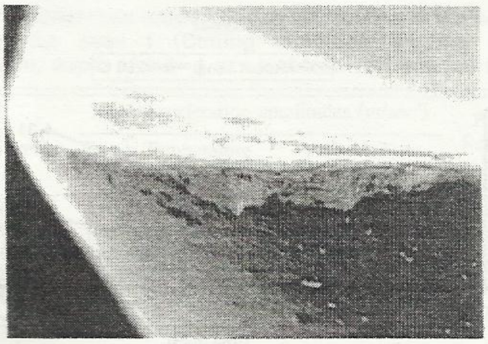


Fig. 10 Pictorial view of the tool nose area after machining at room temperature for case IV (Cutting condition: Cutting speed=300 m/min, depth of cut=2 mm and feed=0.2 mm per tooth)

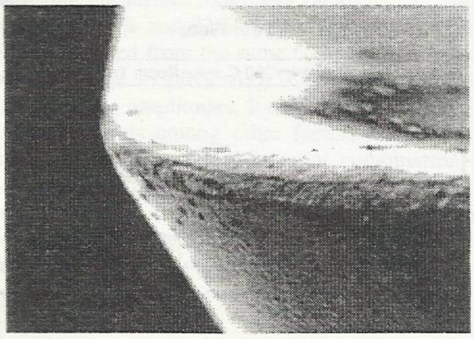


Fig. 11 Pictorial view of the tool nose area after machining at preheated temperature of 260°C for case IV (Cutting condition: Cutting speed=300 m/min, depth of cut=2 mm and feed =0.2 mm per tooth)

after machining with preheating. The cutting speed was 300 m/min and depth of cut and feed were 2 mm and 0.2 mm/tooth respectively. The results of these tests are shown in Table 8.

It may be observed from Table 8 that there is a slight rise in Vickers hardness after machining at room temperature due to strain hardening of the surface layer. In the case of preheating, on the contrary, there is slight softening of the surface layer. The reduction in surface hardness may be due to recovery processes that have taken place at the surface layer. This may contribute to improved machinability of the work material in subsequent cutting operations.

Micrographs of the workpiece material before machining and the machined surface after machining with preheating at the above cutting condition are shown in Figs. 12 and 13 respectively. It may be observed from these figures that the microstructure of the material has not changed except for plastic deformation of the material which has taken place during machining. The machined surface is observed to have experienced no integrity problems. However, small brownish deposits or burs were observed on the machined surface (Fig. 13). These are not bonded to the base metal and may be easily removed by any surface cleaning method. These burs might have contributed to relatively high surface roughness values during preheating.

Table 8 Changes in Vickers Hardness after machining at cutting speed of 300 m/min, depth of cut of 2 mm and feed rate of 0.2 mm/tooth with and without preheating

	Vickers Hardness Number		
Cutting Speed m/min	Before Machining	After Machining at room Temperature	After Machining at 350°C Temperature
300	245.0	251.0	228.0

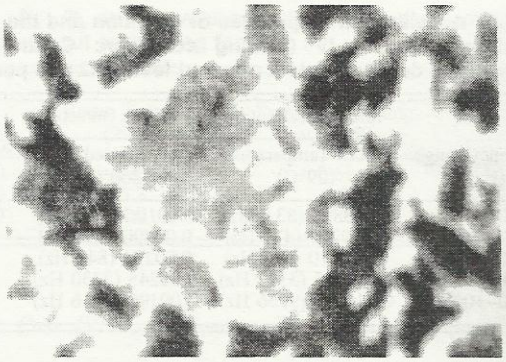


Fig. 12 Micrograph of the workpiece material before machining

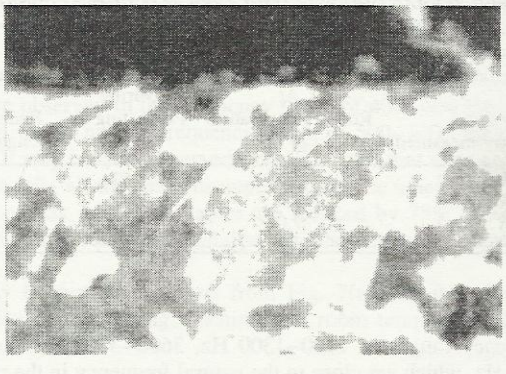


Fig. 13 Micrograph of the machined surface after machining with preheating at 350°C for case I (Cutting condition: Cutting speed=100 m/min, depth of cut=1 mm and feed=0.1 mm per tooth)

Fig. 14 Microstructure of chip after machining at room temperature for case I (Cutting condition: Cutting speed =100 m/min, depth of cut=1 mm and feed=0.1 mm per tooth)

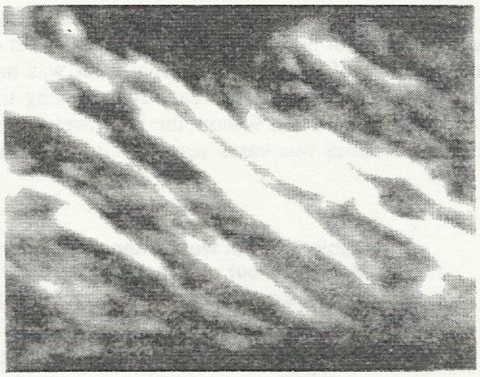


Fig. 15 Microstructure of chip after machining with preheating at 350°C for case I (Cutting condition: Cutting speed =100 m/min, depth of cut=1 mm and feed=0.1 mm per tooth)

The microphotographs of the chips of medium carbon steel after machining at room temperature and with preheating are shown in Figs. 14 and 15 respectively. It is evident from these two figures that the chip thickness is lower in the case of preheating. This indicates that the cutting forces during machining with preheating are lower than that without preheating.

4 Conclusion

The ultimate goal of this research has been to improve machinability of work material by reducing the consequences of chattering arising during machining. The concept of preheating of the workpiece during machining has been introduced to achieve the high machinability objective. Preheating has been performed using induction heating method.

The following specific conclusions have been drawn on the work:

1. Preheating of the workpiece during end milling operation leads to drastic reduction in the amplitude of acceleration of vibration and chatter in a wide frequency range and almost chatter free machining conditions are established in the case of plain carbon steel AISI 1040 machining in a wide range of cutting conditions.
2. Reduction of chatter during preheating is due to reduction of the instability of chip formation and an increase in the plasticity of the workpiece, which results in an improvement in the damping capacity of the system.
3. Preheating of the workpiece increases the tool life by 39% to 52% in the case of AISI 1040 steel.
4. Reduction in surface roughness of the machined part is also observed during preheating. However, the surface roughness can be further improved by an appropriate surface cleaning method to remove the burs deposited on the machined surface during metal cutting with preheating.
5. Machining with preheating practically eliminates strain hardening of machined surface layer due to recovery processes. This may lead to lower cutting forces during the subsequent cutting operations.
6. There is no phase change in the work material during machining with preheating due to the low preheating temperatures employed in the process. Apart from this no surface integrity problem of the machined part during preheating was also observed.
7. Preheating leads to lower chip thickness and correspondingly lower value of shear angle, which is an indication of lower cutting forces during preheating.
8. Induction heating is an efficient method for preheating the workpiece since it is fast, clean and the heat is generated quite uniformly within a thin layer of the workpiece.

Acknowledgment

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