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ORIGINAL ARTICLE

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Investigation of the effects of cooling in hard turning operations

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Abstract As a means to overcome the limitations of cutting fluids in machining, more and more attention is being paid to the internal cooling of cutting tools. The elevated cutting zone temperature in hard turning causes the instant boiling of coolant in the cutting zone, which pulls down the tool life and surface finish, by making thermal distortions and hence in most of the hard turning operations, the coolant is not used at all. The absence of coolant also reduces the tool life and surface finish to some extent. As an alternative solution to the direct application of coolant in the metal cutting zone to improve tool life and surface finish, the heat pipe cooling system is introduced in this investigation. A parametric study is conducted to analyze the effects of different heat pipe parameters such as diameter of heat pipe, length of heat pipe, magnitude of vacuum in the heat pipe and material of heat pipe. All these parameters are varied to three levels. In this analysis, it is assumed that the single point cutting tool is subjected to static heating in the cutting zone which verifies the analysis and feasibility of using heat pipe cooling in turning operations. The heat pipe parameters are optimized by using Taguchi's Design of Experiments and a confirmation test is conducted by employing the heat pipe fabricated with the best values of parameters. The results of the confirmation test are compared with the previous experimental results. The comparison shows that the use of a heat pipe in hard turning operations reduces the temperature field by about 5%, improves tool life by reducing tool wear and improves surface finish significantly. The result of this analysis is applicable to define controlling parameters of heat pipes for optimal design and set-up for various related studies. The finite element analysis also shows that the temperature drops greatly at the cutting zone and that the heat flow to the tool is effectively removed when a heat pipe is incorporated.

Keywords Hard turning · Flank wear · Crater wear · S/N ratio · Heat pipe · Confirmation test · Thermal analysis

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Nomenclature

mm	millimeter
°C	degrees centigrade
kJ	kilojoule
m/min	meter per minute
mm/rev	millimeter per revolution
s	second
V	volt
VA	volt-ampere
Hz	hertz
AC	alternating current
C_p	specific heat
kW	kilowatt
rpm	revolutions per minute
mmHg	millimeters of mercury

1 Introduction

Minimizing the friction between the cutting edge of the tool and workpiece, corrosion control, chip ejection and washing are the functions of cutting fluid [1] in machining. The application of coolant or cutting fluid causes significant contamination to the environment and health hazard for the industrial operators and the disposal of used coolants is also difficult according to the federal, state and local laws and regulations [1]. Approximately 15–25% of total cost of production is spent for coolant [1]. In consideration of environmental pollution and cost of coolants, alternative methods of cooling such as cooling fins [2], heat pipes, etc. are used. In this study, the heat pipe is used to remove the heat accumulated in the tool—workpiece interface [3] as well as in the tool-chip interface in the hard turning operation.

In a metal turning operation, the maximum amount of heat generated in the cutting zone [4] is carried away by chip and the minimum amount of heat is carried away by workpiece, tool, and cutting fluid if used [5]. In the absence of cutting fluid, the heat carried away from the cutting zone is decreased, resulting in an increase in tool and workpiece temperature [5]. The elevated cutting zone temperature significantly shortens the tool life [6], contributes to thermal distortion and poor dimensional accuracy [2] and promotes the formation of built-up edge (BUE) on the tool tip [7].

An effective cooling system, heat pipe, effectively removes the heat from the cutting zone. The heat pipe transports heat energy with a few degrees of temperature difference without the application of any external power supply [5].

Construction wise, the heat pipe is a hollow closed pipe containing a small amount of water in equilibrium with its own vapour and a wick structure on the inner circumferential area of the pipe [1] maintained at a pressure lower than the atmospheric pressure.

The heat pipe has three sections: evaporating section, adiabatic section and condensing section [1]. The evaporating section receives the external heat from the cutting zone and causes the working fluid (water) to vaporize. The vapour reaches the condensing section through the adiabatic section. In the adiabatic section, no heat is absorbed or rejected. The condensing section condenses the vapour and the latent heat of vaporization of the working fluid is rejected into atmosphere. The capillary pressure generated by the meniscus in the wick structure pumps the condensed working fluid [5] back to the evaporating section. The heat transfer continues as long as there is enough heat input [8] in the evaporating section. The heat transfer rate of the heat pipe is much larger than the heat transfer rate of ordinary hollow circular objects of the same specifications because the heat transfer mechanism in the heat pipe is due to the latent heat of vaporization and condensation [9]. The constructional details of a heat pipe are shown in Fig. 1.

For all of the test conditions, the cutting speed, feed rate and depth of cut are constantly maintained at 250 m/min, 0.14 mm/rev and 0.4 mm, respectively. The hard turning operation is conducted without the application of a heat pipe and at the end of every 30 s of machining, the workpiece and tool insert are unloaded from the machine and the flank wear and crater wear of the tool insert are measured by using an optical microscope with these specifications: VERSAMET 3, working distance: 1–5.5 mm, magnification: ×50–1000 and illumination: 12 V, 100 W.

Similarly, the arithmetic average surface roughness value is also measured and recorded with the help of a Mitutoyo Surf III surface tester with these specifications: speed of traverse: 2–5 mm/s, range of traverse: 2–5 mm, driving system: reciprocating motion, line voltage: AC 100–220 V, frequency: 50–60 Hz, accuracy: ±2.5%, power: 2 VA and measuring range: 0.3–100 microns. The machining is continued until the flank wear value reaches 0.2 mm, and all the intermediate values of flank wear, crater wear and surface roughness are measured and recorded. In all of the test conditions, the arithmetic average surface roughness value does not exceed 5 microns. At the end of 465 s of machining, the flank wear reaches 0.193 mm and hence the machining has been stopped since most of the tool fracture occurs with the flank wear of between 0.180 and 0.200 mm. For the purpose of comparison, the turning operations at different test conditions with the application of the heat pipe are also conducted over the same duration of 465 s.

2 Literature review

The metal cutting tools are subjected to an extremely severe rubbing process. They are in metal to metal contact, between the chip and workpiece under conditions of very high stress at high temperatures. Many researchers and scientists developed a lot of thermal models to analyze the temperature gradients in the cutting tools. An investigation of heat pipe cooling in drilling applications was presented by Jen et al. [1]. Zhao et al. [2] demonstrated the effects of internal cooling on flank wear in orthogonal metal cutting. Ackroyd et al. [3] investigated the contact conditions in machining. Micro-cooler for chip-level temperature control was studied by Yerkes and Dorian [4]. Chiou et al. [5] analyzed the effects of an embedded heat pipe system in machining operations. Ko et al. [6] analyzed the air-oil cooling system in turning operations. Different microstructures in continuous and intermittent cutting were studied by Chou [7]. A thermal model was developed and presented by Chou and Evans [8]. The heat transfer behaviour of carbide inserts with heat pipe application was studied by Chiou et al. [9]. Thermal performance issues for a metallic thermal protection system were presented by Blosser [10]. Potdar and Zehnder [11] demonstrated the techniques of measuring and simulating the temperature field in transient metal cutting. Huang et al. [12] modelled the effects of tool thermal properties in hard turning. Dawson and Kurfees [13] investigated the tool wear and surface quality in hard turning. Liu and Mittal [14] described the various factors affecting surface quality. Narayanan et al. [15] demonstrated the technique for tool-chip interface temperature measurement. The effect of vis-

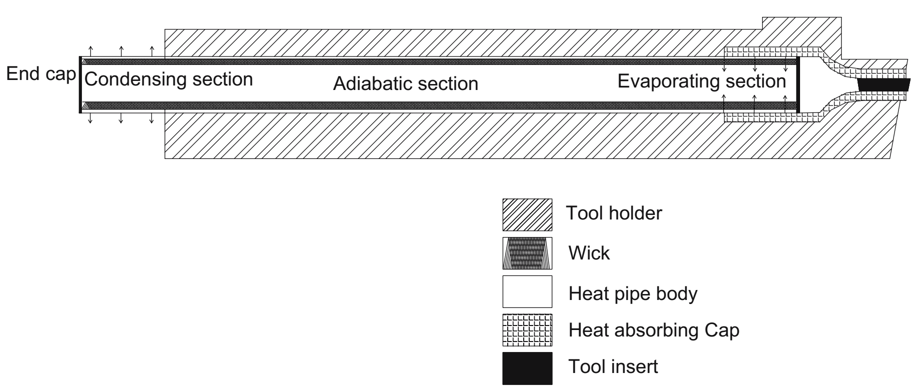

Fig. 1 Cut section of heat pipe arrangement

coplasticity in predictive modelling of chip flow was well defined by Leopold [16]. The bonding strength and tool life of CBN inserts were compared by Takastu et al. [17]. The method of decreasing machining time and reducing the number of machines required in cases of hard turning instead of conventional grinding was described by Konig et al. [18]. Kopac et al. [19] presented the analysis of machining parameters in a turning process. The various responses of cutting temperature on flank wear was presented by Young [20]. Wanigarathne et al. [21] presented an experimental solution for cutting temperature distribution in a turning operation. Bendell [22] presented the various applications of Taguchi's method of optimization. Ghani et al. [23] optimized and presented the end milling parameters. The spring-back effect of sheet metal work was optimized by Tekiner [24]. Feng [25] explained the various parameters affecting surface roughness of a turned surface. A temperature rise distribution due to shear plane heat source was modeled by Komanduri and Hou [26]. Temperature rise distribution due to frictional heat source at tool-chip interface was modelled and demonstrated by Komanduri and Hou [27]. Komanduri and Hou [28] modelled the temperature rise distribution due to the combined effects of shear plane heat source and tool-chip interface frictional heat source. Baker [29] investigated the chip segmentation process using finite elements. In most of the available previous works, the performances of various alternative cooling systems were compared with the performance of conventional cutting fluids. In this work, the heat pipe controlling parameters are optimized and the experiments are conducted with a heat pipe designed with the optimized values of parameters.

3 Preliminary experimental analysis

To examine the thermal properties [10] and suitability of a heat pipe for the validity of the heat transfer from the CBN insert with the application of a heat pipe, four different preliminary experiments are conducted on copper pipe, steel pipe, brass pipe and brass heat pipe. The required preliminary experimental set-up is shown in Fig. 2.

Four numbers of 0.1 mm diameter K-type thermocouples [11] are fixed at different vertical locations (t_1, t_2, t_3 and t_4) in the cooling chamber and one end of the test specimen is electrically heated and maintained at 100°C as shown in Fig. 2. The amount of heat transferred from the heating end to the cooling end of each specimen over a period of 5 min is calculated using the expression:

$$\text{Heat transfer, } Q = m_w c_{pw}(t_f - t_i)\,\text{kJ}$$

where

m_w	Mass of water in the cooling chamber (0.5 kg)
c_{pw}	Specific heat of water (4.187 kJ/kg K)
t_f & t_i	Final and initial temperature values (in Kelvin) of water in the chamber (t_1+t_2+t_3+t_4/4)

Hence the heat transfer through

Brass pipe	0.5×4.187(39–30)=18.8 kJ
Copper pipe	0.5×4.187(36–30)=12.6 kJ
Steel pipe	0.5×4.187(35–30)=10.5 kJ
Brass heat pipe	0.5×4.187(54–30)=50.2 kJ

From the preliminary experimental results, it is understood that the heat transfer rate [12] of the heat pipe is much higher than that of the other ordinary pipes.

4 Experimental details

The required hard turning operations [13] are performed on a lathe which is specified as 177.5 mm centre height, 520 mm swing gap, 1600 rpm speed, 0.05–3.5 mm/rev of feed range and main motor power of 3.7 kW. The geometry of the selected CBN cutting tool inserts [12] is 80° diamond shape with 20° edge chamfer, 0.102 mm wide and 12 mm×12 mm×4 mm size. The tool holder of size 32 mm square is used.

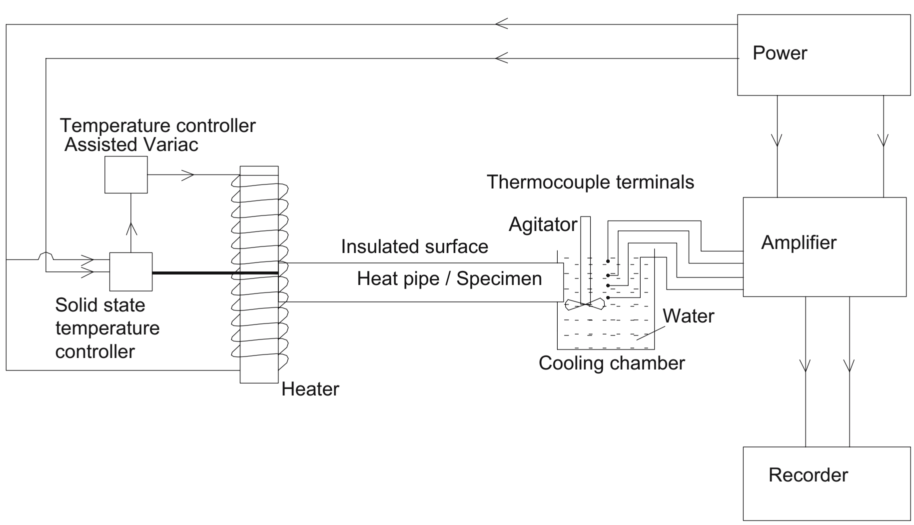

Fig. 2 Preliminary experimental set-up

Table 1 Experimental test conditions and measured data for 465 s of machining

Test condition numbers	Heat pipe parameters				Tool wear		S/N ratio	
	Length (mm)	Diameter (mm)	Vacuum (mmHg)	Material	Flank wear (mm)	Crater wear (mm)	Flank wear	Crater wear
1	20	5	300	Brass	0.191	0.104	14.38	19.66
2	20	7	350	Steel	0.189	0.103	14.47	19.74
3	20	10	400	Copper	0.187	0.101	14.56	19.91
4	30	5	350	Copper	0.188	0.102	14.52	19.83
5	30	7	400	Brass	0.183	0.097	14.75	20.26
6	30	10	300	Steel	0.190	0.103	14.42	19.74
7	40	5	400	Steel	0.185	0.099	14.66	20.08
8	40	7	300	Copper	0.186	0.100	14.61	20.00
9	40	10	350	Brass	0.184	0.098	14.70	20.18

In the heat pipe arrangement, the heat absorbing insert cover is designed to have a circular tube-like construction (cap) at one end in order to accommodate the heat absorbing section of the heat pipe as shown in Fig. 1. In the gap between the cap inner wall and heat pipe outer wall, thermal grease [5] is applied to avoid convection and to improve conduction. For simplicity it is considered that heat is transferred from the outer cylinder (heat absorbing cap) to the inner cylinder (heat pipe) neglecting the effect of thermal grease.

The outermost layer of the workpiece of engine crank pin material selected as specimen is turned off first by using mixed alumina cutting insert [13] in order to avoid the hard turning of the oxidized layer. In this analysis, four parameters at three levels each are considered for parametric optimization [14] based on thermal aspects [15]. The various levels (1, 2 and 3) of controlling parameters selected are:

Length of heat pipe inserted into the heat absorbing cap: 20 (1), 30 (2) and 40 (3) mm
Inner diameter of heat pipe: 5 (1), 7 (2) and 10 (3) mm
Material of heat pipe: copper (1), steel (2) and brass (3)
Magnitude of vacuum in the heat pipe: 300 (1), 350 (2) and 400 (3) mm of mercury

At a particular cutting condition as shown in Table 1, the hard turning operation is performed and at regular intervals of 30 s, the tool wear and surface roughness [16] are measured. At the end of 465 s of machining, the turning operation is stopped because most of the tools fracture with the flank wear of between 0.180 and 0.200 mm [17]. Similarly, the other turning operations with different cutting inserts [18] at different cutting conditions as shown in Table 1 are also performed for the same duration of 465 s and the flank wear, crater wear and surface roughness values are recorded. The rows of the table represent the test conditions and the columns represent the heat pipe parameters, tool wear and the S/N ratios. As per Taguchi's technique, the minimum number of experiments to be conducted for parametric optimization is calculated as:

$$[(\text{Number of levels} - 1).\text{Number of parameters}] + 1 = [(3 - 1) \times 4] + 1 = 9.$$

The calculated number of experiments with different test conditions are performed and the heat pipe parameters are optimized. The optimized values of parameters [19] are confirmed by conducting a confirmation test.

In this study, with the application of the heat pipe designed as per the confirmation test result, the temperature values at various locations of cutting tool inserts [20] are measured by placing the 0.1 mm diameter K-type of thermocouples [15]. The first thermocouple is located at 2 mm from the tip of the tool insert and all other thermocouples are located linearly with an increment of 1 mm each in the same direction. Due to

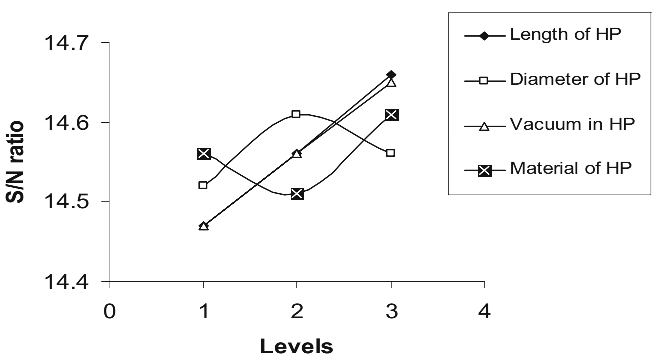

Fig. 3 S/N curves for flank wear of cutting insert

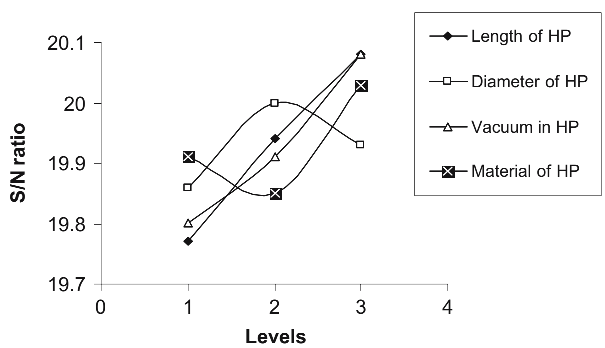

Fig. 4 S/N curves for crater wear of cutting insert

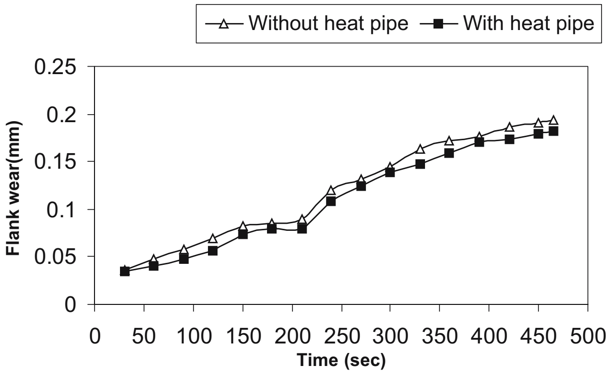

Fig. 5 Comparison of flank wear of tool insert with respect to machining time

the edge effects, the temperature values measured are lower than the actually occurring tool tip and bulk temperatures [20]. To compensate for this deviation, the experimentally calculated correction factor is included in the calculation of tool tip temperature [21]. By interpolating the temperatures measured with thermocouples, it is possible to obtain more temperature values from the cutting tip to the opposite extreme end.

5 Results and discussion

The heat pipe cooling system has been considered as an alternative to flood cooling [1] in this work. The tool life and surface quality of a hard turned surface is expected to be better than the tool life and surface quality [10] obtained in the existing flood cooling system.

The statistical measure of performance called signal to noise (S/N) ratio developed by Taguchi [22] is applied to determine the effects of various heat pipe controlling parameters on flank wear, crater wear and surface quality. The best set of parameters has been identified for the hard turning operation. The S/N equation depends on the criterion for the quality characteristics to be optimized [23]. In this analysis, the tool wear is required to be minimized. So, the smaller-is-best formula for S/N ratio [23] is selected

$$^{S}/_{N}\,ratio = -10\log_{10}\frac{1}{n}\left[\sum\bar{y}^{2}\right]$$

where n is the number of trials of experiments (=1) and $\bar{y}$ is the sum of square of the measured data.

For example, the S/N ratio for flank wear based on first test condition (Table 1) is calculated as

$$\mathrm{S/N\ ratio} = \left[-10\times\log_{10}0.191^{2}\right] = 14.38.$$

Similarly, by using the above formula, the S/N ratios for all the flank wear and crater wear of inserts are calculated and tabulated in Table 1. For identifying the individual effects [24] of various parameters on the objectives, the S/N ratios are calculated individually. For example, the individual effect of length of the heat pipe on tool wear corresponding to 40 mm is calculated as

$$\text{Flank wear} = \left(\frac{\text{Flank wear values corresponding to 40mm of heat pipe length}}{3}\right)$$

$$\text{Flank wear} = \left(\frac{0.185+0.186+0.184}{3}\right) = 0.185\ mm$$

$$\text{Crater wear} = \left(\frac{\text{Crater wear values corresponding to 40mm of heat pipe length}}{3}\right)$$

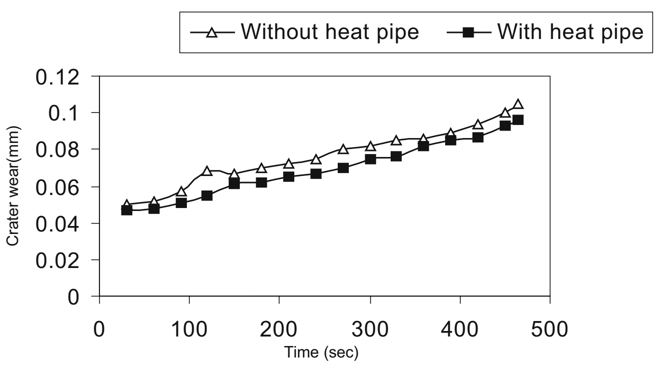

Fig. 6 Comparison of crater wear of tool insert with respect to machining time

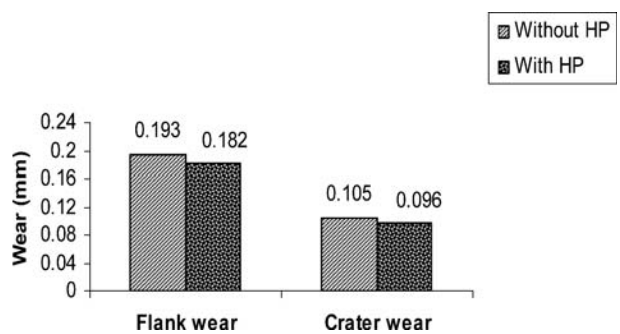

Fig. 7 Comparison of flank wear and crater wear at the end of 465 s of machining

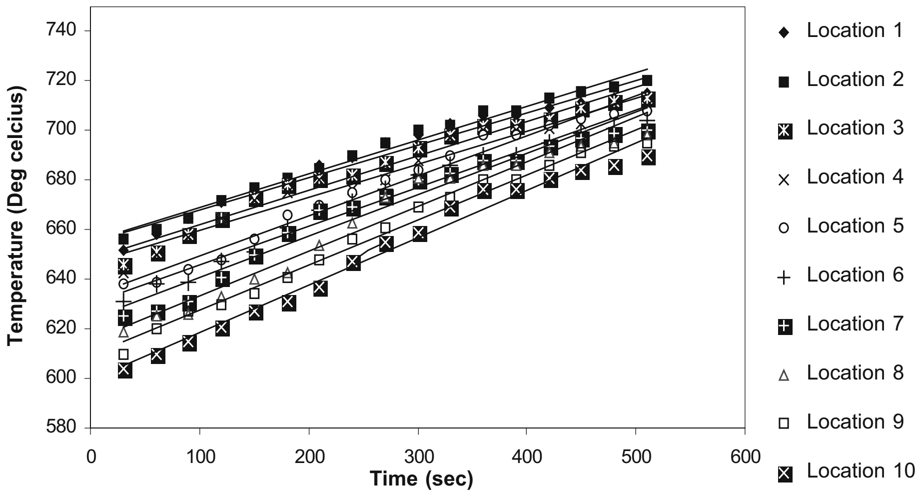

Fig. 8 Temperature variations at different locations of tool insert with respect to machining time

$$\text{Crater wear} = \left(\frac{0.099 + 0.100 + 0.098}{3}\right) = 0.099\,mm$$

Similarly, the effects of individual parameters on flank wear and crater wear of tool insert are calculated and graphically represented in Figs. 3 and 4. From Figs. 3 and 4, the maximum values indicated by the S/N curves are identified as best values of heat pipe parameters for minimizing the tool wear. The identified best values of heat pipe parameters are:

Length of heat pipe	40 mm
Diameter of heat pipe	7 mm
Heat pipe vacuum	400 mmHg and
Heat pipe material	Brass

With the above identified best values of heat pipe parameters, a new heat pipe is fabricated, employed and the required hard turning operation is performed with the selected constant process parameters as a confirmation test. The results obtained are 0.182 mm of flank wear and 0.096 mm of crater wear which are lower than the previous experimental values shown in Table 1. Thus the best values of heat pipe controlling parameters are confirmed.

The results of the experiments conducted without the application of any heat pipe show that the flank wear and crater wear values are 0.193 mm and 0.105 mm, respectively, which are not shown in Table 1. The minimum values of flank wear and crater wear are 0.183 mm and 0.097 mm when the randomly selected heat pipe is employed, which are shown in Table 1.

The flank wear values of the cutting tool with and without the application of the heat pipe with respect to cutting time are measured and shown in Fig. 5. Similarly, the values of crater wear of the cutting tool with and without the application of the heat pipe with respect to time are shown in Fig. 6. From Fig. 7, it is observed that the application of the heat pipe reduces flank wear and

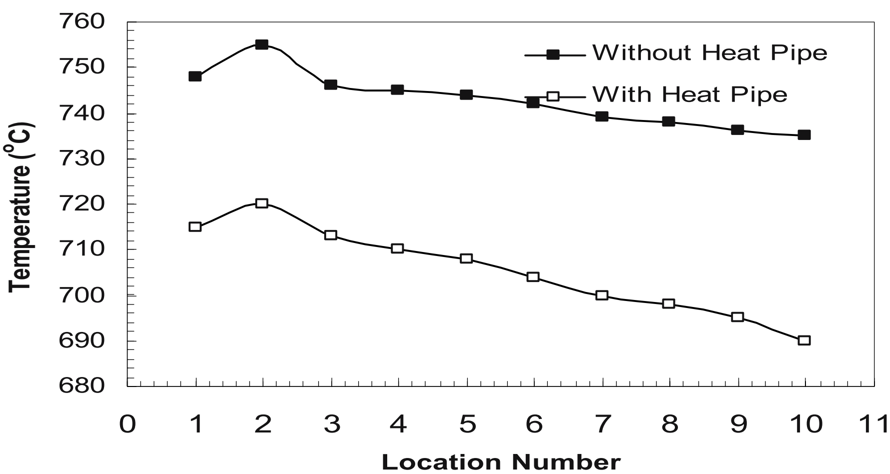

Fig. 9 Comparison of temperature of the tool insert at different locations at the end of 465 s of machining

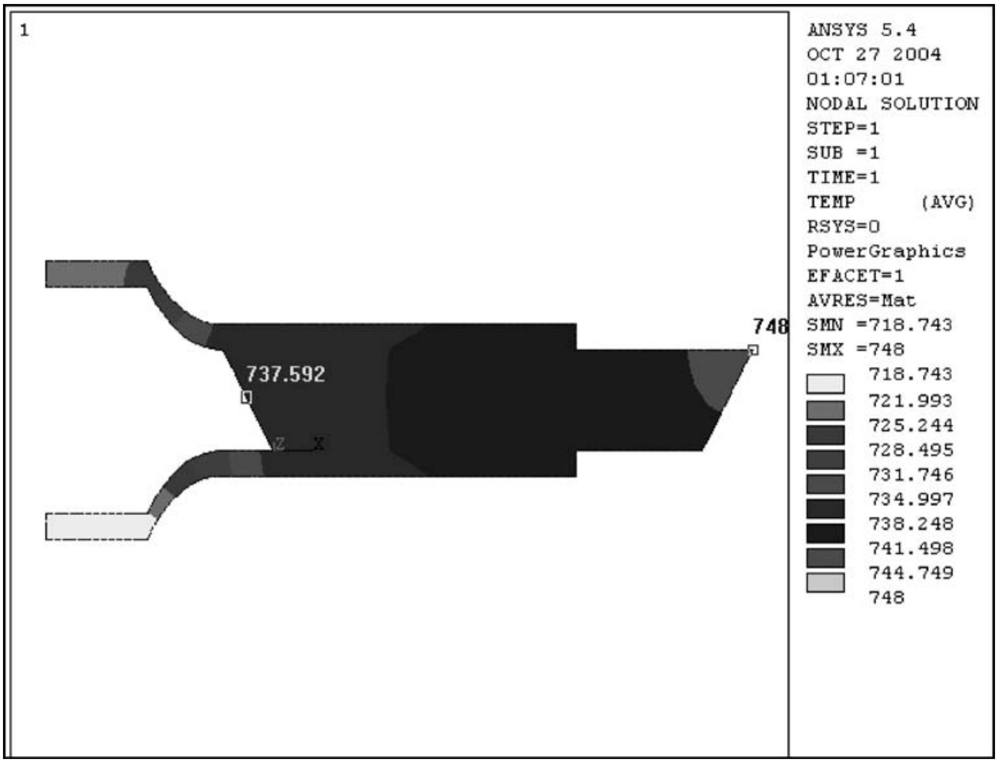

Fig. 10 Temperature distribution in the tool insert without heat pipe

crater wear of cutting tool inserts significantly by about 5.7% approximately 6% [=(0.193–0.182)×100/0.193] and 8.6% approximately 9% [=(0.105–0.096)×100/0.105], respectively. In all of the test conditions, the arithmetic average roughness value of turned surfaces [25] does not exceed 5 microns. With the measured values, the required thermal analysis [26–28] is carried out in hard turning.

The temperature values at different locations of tool insert with respect to machining time with the application of the same heat pipe are recorded and graphically shown

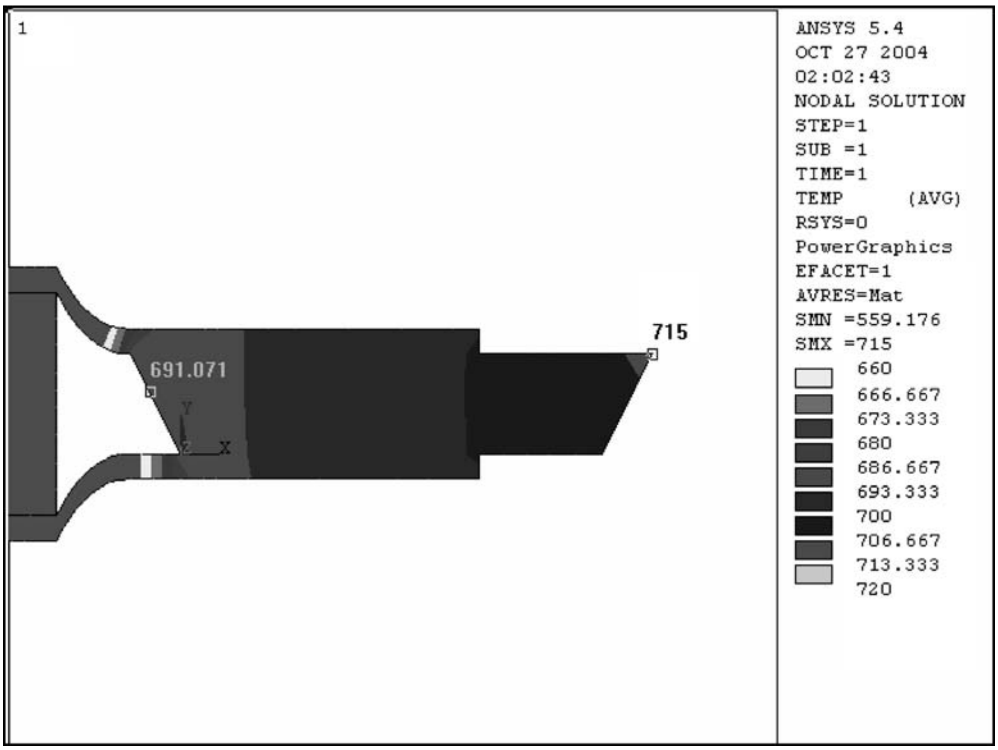

Fig. 11 Temperature distribution in the tool insert with heat pipe

in Fig. 8. Due to the heavy rubbing action of the chip on the rake face of the tool, the temperature value at the second location is higher than the temperature values at all other locations as shown in Fig. 8.

Figure 9 shows that the presence of the heat pipe drops the temperature values significantly at various locations of the tool insert at the end of 465 s of machining which improves the tool life to a considerable extent.

To examine the experimental temperature distribution in the cutting insert, the maximum temperature of the cutting zone with and without the application of the heat pipe are simulated. Figure 9 shows that the experimental temperature of the tip of the tool insert is 748°C at location 1 and drops gradually to 736°C at location 10 when the heat pipe is not employed and the temperature of the tool tip is 715°C at location 1 and the temperature gradually decreases to 690°C at location 10 when the designed heat pipe is employed.

The experimental result shows that there is a temperature drop of 25° when the designed heat pipe is employed.

For the verification and confirmation of this temperature drop when the heat pipe is employed, the temperature distribution is simulated by using finite element analysis (FEA). The FEA results given in Figs. 10 and 11 show that the temperature values at locations 1 and 10 without the application of the heat pipe are 748°C and 737°C, respectively, and in the presence of the heat pipe, the temperature values are 715°C and 691°C, respectively.

The FEA result shows that 24° of temperature is dropped when the heat pipe is applied. Since two-dimensional simulation is carried out in this work, the simulated temperature values slightly deviate from the experimental values.

Since the FEA result is more or less the same as that of the experimental result, it is confirmed that the experimental data are significant.

However, this FEA simulation [29] shows that the installed heat pipe has a significant effect on the reduction of cutting zone temperature.

From the preliminary experiments and FEA, it is clear that the heat generated in machining is effectively removed [29] by the heat pipe in order to improve tool life and surface quality.

6 Conclusion

The tool wear strongly depends on cutting temperature. The experimental result demonstrates that the heat from the cutting zone is effectively removed by the installed heat pipe.

The flank wear and crater wear of the cutting inserts are significantly reduced by about 6 and 9%, respectively, by lowering the temperature of the cutting zone well below the softening temperature of inserts.

The application of the heat pipe completely eliminates the application of cutting fluids in hard turning with a considerable reduction of tool wear and improvement of surface finish. This analysis provides valuable information on the alternative of heat pipe cooling in hard turning operations.

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