A novel approach to use internally cooled cutting tools in dry metal cutting

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This paper presents a new cooling method to be used in dry metal cutting. This new cooling method is based on a tool holder with cooling fluid circulating inside a closed internal cooling system. A prototype that facilitates the cooling from inside the tool holder was specifically designed and manufactured. For this study, a series of cutting trials was carried out to investigate the practicality and effectiveness of the internally cooled cutting tool concept. Two techniques, one using a K-type thermocouple and the second using an infrared (IR) pyrometer, were employed to estimate the temperatures of the tool and the tool-chip interface. Experiments were conducted on DIN 1.2379 cold work die steel (50 HRC) using CVD-coated CNMG 190608-IC907 carbide inserts. The experimental results for dry cutting and for the internally cooled tool were compared using fluid dynamic analysis implemented via the ANSYS Fluent FEA code. The internally cooled tool exhibited the advantages of better surface roughness and extended tool life; in addition, machining was enabled at a wider range of cutting speeds while avoiding environmental hazards and health problems. The results clearly indicated that internal cooling could sufficiently reduce the cutting temperature and consequently, by controlling the critical cutting temperature, was able to circumvent it during the turning process. This technique could generally be advantageous for the machining of hard materials.

Keywords: Internal cooling, Tool life, Metal cutting, Coolant fluid, Tool holder design

The major requirements in machining are higher material removal rate, better surface finish and lower energy consumption. These objectives can be achieved by reducing tool wear with the use of a proper tool cooling system during machining. In the machining process, a considerable amount of energy is transformed into heat through plastic deformation resulting from chip formation, friction between the chip and the tool face and friction between the tool and the work-piece[1,2]. Most of this heat energy is carried away by the chip; the rest is transferred to the tool, to the work-piece and to the environment. The heat transferred to the tool mainly reduces either the mechanical resistance or the wear resistance of the tool[3]. Maximum temperatures arise in the contact zone between the chip and the tool. The temperature distribution depends on the heat conductivity and specific heat capacity of the tool and the work-piece. In the turning operation, friction and heat generation at the cutting zone are frequent problems affecting tool life and surface roughness[4-6]. The heat generation rate, Q (W), is given by Sata and Takeuchi[7,8] as: $Q = 1.68af^{0.15}V^{0.85}$, where a is the depth of cut (mm), f is the feed rate (mm/rev), and V is the cutting speed (m/min).

In dry cutting operations, friction and adhesion between the chip and the tool tend to be higher, causing higher temperatures, higher wear rates and, consequently, shorter tool lives. At present, completely dry cutting is not recommended for many machining processes due to the necessity of using cutting fluid to prevent the chip from adhering to the tool[9,10].

In the machining process, cutting fluids have been used for many years to reduce the temperature during machining, having the effect of reducing tool temperature, improving tool life and product quality; however, cutting fluid use can result in environmental pollution, health hazards and high production costs[11-13]. Cutting fluids are beneficial in minimizing the length of the chip contact with the cutting tool, reducing the cutting temperature, decreasing the cutting force, improving tool life and work-piece surface conditions, reducing work-piece thermal deformation and flushing away chips from the cutting zone[14-16]. Dhar et al.[17], investigated the use of cutting fluids has some disadvantages, including added costs involving storage needs, pumping, filtering and recycling, and potential operator health problems caused by gases, fumes and bacteria formed in the cutting fluids. Furthermore, cutting fluids pose a risk of skin cancer after long exposure. The need for green cooling

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methods that do not harm the environment or risk the health of operators and at the same time are efficient in removing heat from the cutting zone have been repeatedly sought after[17]. Sreejith and Ngoi[18], suggested a method involving indirect contact of the coolant with the cutting zone as an alternative to dry machining. In their system, the use of an internal cooling system was introduced in which the coolant flowed through channels under the insert, without having direct contact with the cutting zone[19]. Shu *et al.*[19], studied a novel approach for measuring the cutting temperature during the process and controlling it to some extent by using an internally cooled smart cutting tool with a closed internal cooling circuitry. The innovative smart tooling design concept could effectively sense the cutting temperature in process at the cutting insert edge and could also be used to reduce and control the critical cutting temperature in the cutting zone[19].

Vicentin *et al.*[4], used a cooling system in turning for a cutting tool based on a tool holder with cooling fluid circulating inside. In that study, R-123 was selected as the cooling fluid for the machining of austenitic steels of low machinability. The developed system resulted in a surface roughness up to 10% better than that of dry machining. The main concept of that study was to eliminate the amount of cutting fluid used in machining operations and to avoid environmental and health problems, as well as to reduce costs, by maintaining tool wear within acceptable limits and by using low consumption methods[4]. An internally cooled cutting tool was analyzed and designed for dry cutting by Sun *et al.*[11]. The cutting tool was characterized by a simple, replaceable internal cooling structure near the cutting tip. Simulations were done to study the theoretical cooling efficiency and to optimize the cooling structure by combining it with the Taguchi method[11]. Zhao *et al.*[20], carried out a numerical simulation of internal cooling using an internal device, and revealed that it was possible to reduce cutting temperature and flank wear. Ghani[21], investigated internally cooled cutting tool designs and found that, by preventing chip contamination as well as lowering the cutting temperature, internal micro-cooling was an environmentally sound method.

In this paper, a novel approach is presented that uses an internally cooled tool holder with cooling fluid circulating inside. A prototype that facilitates the cooling from inside the tool holder was specifically designed and manufactured. It was designed for the highest cooling capacity of the contact area between the bottom surface of the insert and the slots. A series of cutting trials was carried out to investigate the practicality and effectiveness of this internally cooled tool holder concept and the results were compared with those of dry cutting.

Experimental Procedures

Design and production of the tool holder
The idea of an internally cooled tool holder began with the recognition of the needs and desires of those who will use the product, in particular the demand for economical high-quality machining and efficient eco-friendly manufacturing[21]. The internal structure of the tool holder was designed to be as close as possible to the cutting edge in order to achieve the highest heat transfer rate. Two holes for inlet and outlet circulation of the coolant were drilled into the tool holder. The slots and holes on the tool holder are shown in Fig. 1. Cooled water was pumped continually from a container of pure water to the inlet and back to the container from the outlet forming a closed-loop internal cooling system. A schematic view of the tool holder and cutting insert is shown in Fig. 2. To avoid coolant leakage, O-ring seals were used at the flow channel between the insert and the tool holder. The design was created primarily by CATIA computer-aided design (CAD) software, and the channel was manufactured precisely using a CNC milling machine.
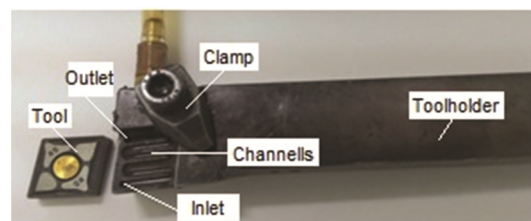
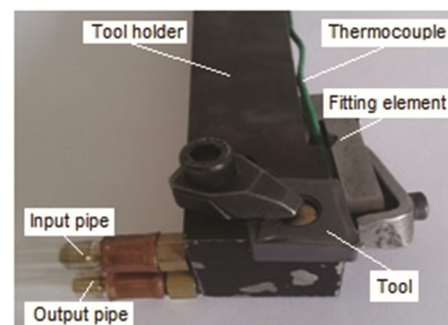

Fig. 1 — Slots and holes on the tool holder

Fig. 2 — Schematic view of the tool holder and cutting insert

Internal cooling framework

A prototype that facilitates cooling from inside the tool holder was specifically designed and manufactured. It was designed for the highest cooling capacity of the contact area between the bottom surface of the insert and the slots. As there is a particularly high surface roughness in the slots, the aim was to maximize the cooling effect. A conceptual illustration of the internally cooled tooling structure is shown in Fig. 3. Owing to its high specific heat capacity, water was provided as the coolant. In order to prevent the metallic parts from oxidizing in the water, corrosion inhibitors were added.

Work-piece material and the cutting tool

The work-piece material was AISI D2 (DIN 1.2379) cold work tool steel having the chemical composition of 1.55% C, 11.80% Cr, 0.80% Mo, 0.80% V, 0.30% Si, and 0.40% Mn. Cylindrical samples (Ø45 × 300 mm) were heat treated using the induction hardening process, maintaining a hardness of 50 HRC. After heat treatment, the samples were normalized. In the experimental
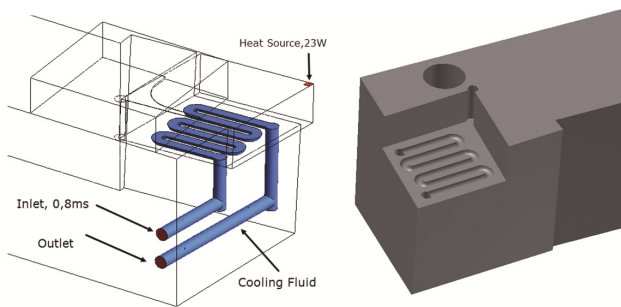

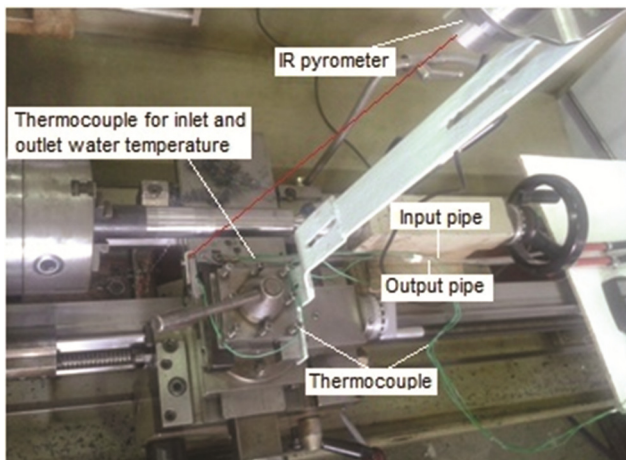Fig. 3 — Conceptual illustration of the internally cooled tooling (a) structure and (b) water pipeline

Fig. 4 — The experimental set-up connection on the lathe

trials, a CVD-coated CNMG 190608-IC907 carbide insert were used.

Experimental set-up

A series of cutting trials was performed in order to investigate the practicality and effectiveness of the proposed internally cooled tool holder. A details of the experimental set-up are given in Table 1.

An Optris CF4 IR (infrared) pyrometer was used to monitor the tool-chip interface temperature and OPTRIS PI software was used to display the images and the measured temperature values dynamically. The infrared pyrometer served as the calibrated standard device for determining the transfer factors. The emissivity value of 0.60 was determined on the CVD-coated tungsten carbide surface for the temperature range of 385°C-1600°C. The measurement point was 1.5 mm in size, corresponding to the distance to the 0.6 mm measurement surface[22].

Five measurements were recorded by the pyrometer in every second. Each experiment was

Table 1 — Experimental setup

| Machine	Harrison M300
Work specimen's materials	AISI D2 (DIN 1.2379)
Size	Cylindrical work pieces Ø45×300 mm
Cutting tool	CVD coated carbide CNMG 190608
Tool holder	Designed for internal cooling
Cooling fluid	Pure water
Cooling equipment	Employed for cooling fluid circulation
Tool-chip interface temperature	Optris CF4 infrared pyrometer
Tool temperature	Type K thermocouples
A profilometer	TIME TR200 Surface roughness tester
Microscope	Nikon104 with a magnification of X10
Cutting speed	80 m/min, 113 m/min, 170 m/min
Feed rate	0.08 mm/rev
Depth of cut	0.50 mm
Inlet fluid velocity	0.8-1.6 m/s
Environment	Dry and internally cooled tool holder
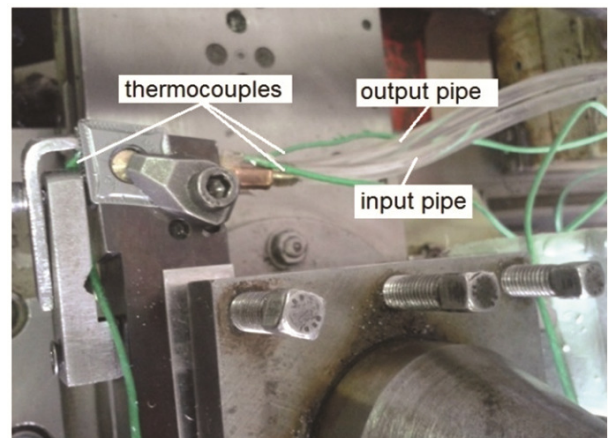
Fig. 5 — Thermocouple mounting

repeated three times at the same cutting conditions and the measured values were averaged. The accuracy of the system was ± 0.3% for a reading of + 2°C. A typical image obtained with the thermocouple and IR pyrometer is shown in Fig. 4, where the maximum cutting temperature is located at a position near the center of the tool-chip contact face. It was assumed that the average cutting temperature was located at the center of the tool-chip interface[3].

The tool temperature was measured using a K-type thermocouple having a data acquisition system of ± 2.5°C or ± 1%. The mounting of the thermocouple is shown in Fig. 5.

Results and Discussion

Effectiveness of internal cooling and temperature reduction

Using a conventional lathe, a series of cutting trials was carried out to investigate the practicality and effectiveness of the proposed internally cooled tool holder. Water was used as the cooling fluid in the experiments. Comparisons of temperatures for dry and internally cooled conditions are given in Table 2. For all conditions, when the inlet velocity was more than 1.0 m/s, tool temperature decreased slightly. It was

found that the temperature differences between inlet and outlet decreased with the increase in flow rate.

The maximum tool-chip interface temperature was observed to decrease from 607°C to 545°C with internal cooling. This clearly indicated that internal cooling could sufficiently reduce the cutting temperature and enable the cutting tool to work while avoiding the critical cutting temperature by controlling it during the process, which is vitally
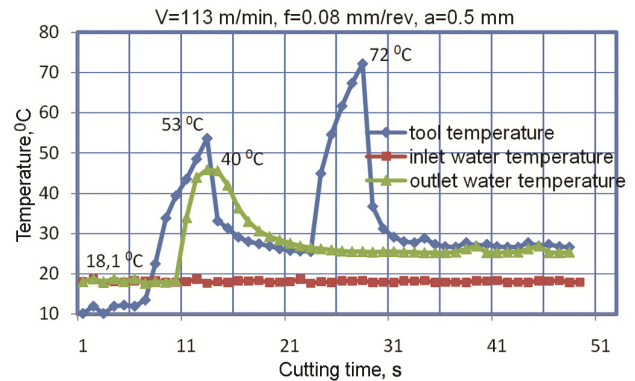

Fig. 6 — The tool temperature differences for dry and internally cooled tool holders (K-type thermocouple at 1 kHz frequency and response time is 200 ms)

Table 2 — Comparisons of tool-chip interface and tool temperatures for dry and internally cooled conditions ($f = 0.08$ mm/rev, $a = 0.5$ mm)

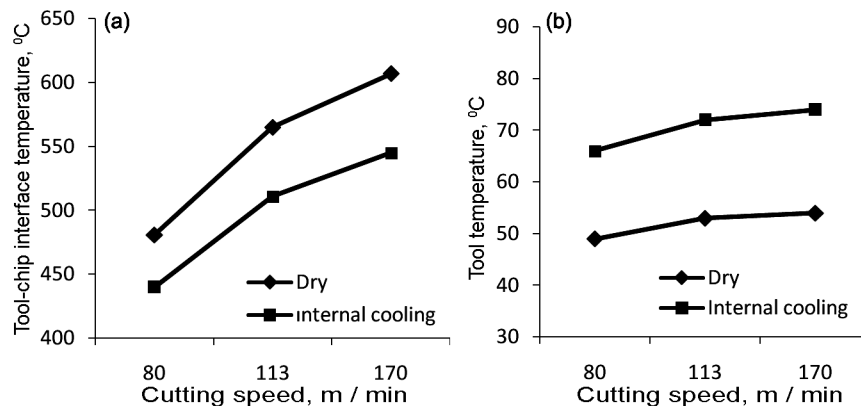|	V m/min	Tool-chip interface temperature (°C)			Tool temperature (°C)			
		Inlet velocity m/s	Dry	Internally cooled	Temperature difference (°C)	Dry	Internally cooled	Temperature difference (°C)
01	80	0.8	481	450	31	66	54	12
02	80	1.2	481	447	34	66	52	14
03	80	1.6	481	440	41	66	49	17
04	113	0.8	565	520	45	72	58	14
05	113	1.2	565	516	49	72	56	16
06	113	1.6	565	511	54	72	53	19
07	170	0.8	607	556	51	74	59	15
08	170	1.2	607	552	55	74	57	17
09	170	1.6	607	545	62	74	54	20

Fig. 7 — Temperatures at different cutting speeds (a) tool-chip interface temperature and (b) tool temperature
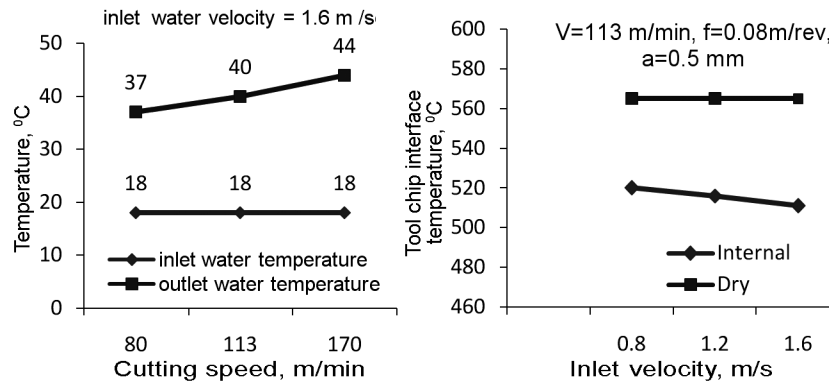
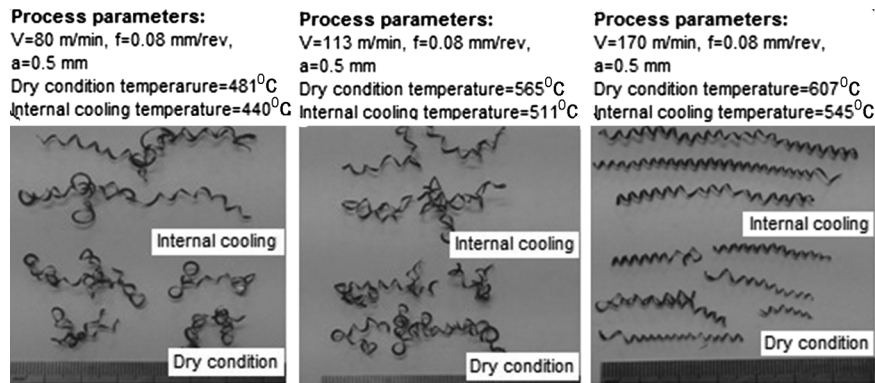Fig. 8 — Temperature differences of inlet and outlet water

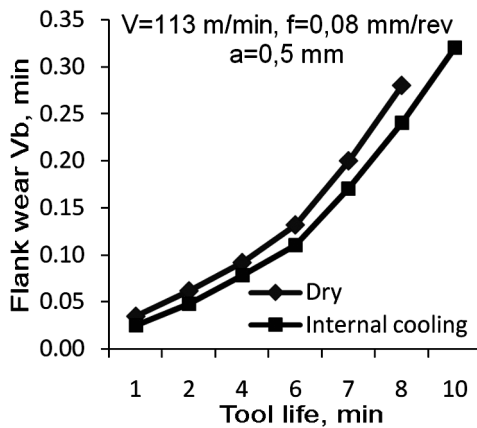Fig. 9 — Chip formations at dry and internal cooling conditions

Fig. 10 — Comparisons of flank wear for internal cooling and dry conditions

Fig. 11 — Surface roughness comparisons for various cutting speeds

important in extending tool life during the machining of hard materials[19]. By using internal cooling, it is possible to determine the critical temperature that will bring about rapid tool failure. Figures 6 and 7 show the temperature difference for the dry and internally cooled tool holders at various cutting speeds, and inlet cooling fluid velocities.

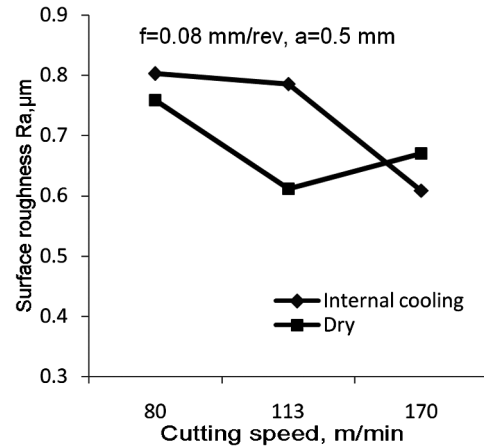The internally cooled tool was effective in reducing the tool and tool-chip interface temperatures at all cutting speeds. There were linear correlations between the temperature and the cutting speed, even when the flow rate of the coolant was low. Figure 8 shows the temperature differences of the inlet and outlet water.

The internal cooling method not only affected the temperature but also affected the chip forms as well. Under dry cutting conditions, temperatures at the tool-chip interface increased. In Fig. 9, chips

produced under dry and internal cooling conditions can be seen. At the same cutting parameters, but with changes in temperature, differences were observed in the chip form during both dry and internally cooled machining. In dry cutting, the chip was shortened and broken up; however, the chip was longer when internal cooling was applied and the temperature was decreased, affecting the surface roughness positively. At higher temperatures, the chips were longer and formed tight curls; the exact opposite was observed at low cutting speeds.

Temperature correlation with flank wears and tool life

The use of coolants to maintain constant cutting temperatures is an important factor in the extension of cutting tool life. This situation is generally beneficial in the machining of hard materials[11]. As the wear mechanism is affected by the cutting temperature, low cutting temperatures can minimize the development of tool wear. The experimental trials indicated that by using an internally cooled tool, the temperature was controlled as well as the wear mechanism, and thus, tool life was extended and better surface quality was obtained. According to the experimental results, it was possible to extend the tool life up to 15% by the use of the internal cooling method. Flank wear and tool life for the internally cooled and dry conditions are shown in Fig. 10.

Measurements of surface roughness

A series of experiments was conducted at different cutting speeds and the surface roughness values were measured using a portable TIME TR200 device which was adjusted to a cut-off length of 0.8 mm and a traverse speed of 1 mm/s. After each turning test, the surface roughness was measured at intervals of 120° on the outer diameter, and the average values
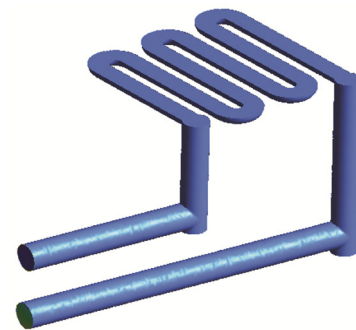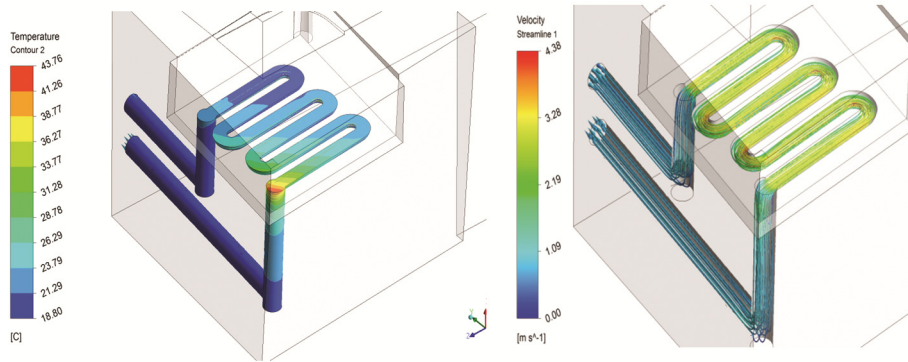

Fig. 12 — Cooling water pipeline

Fig. 13 — Fluid dynamics model and fluid velocity distribution (a) temperature and (b) velocity stream line
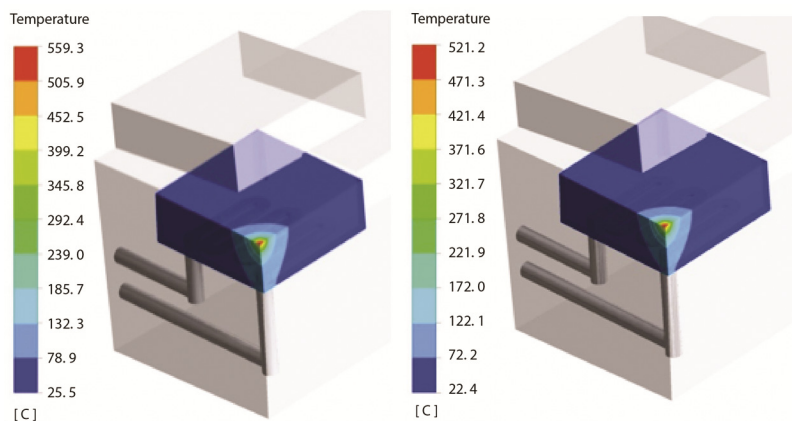

Fig. 14 — Tool holder temperature distribution for dry and internally cooled simulations

Table 3 — FEA model input values for the cutting tool

Insert thickness	4.00 mm
Tool holder length	120.00 mm
Tool holder width and height	20.00 mm
Thermal conductivity of insert	112.5 W/m.K
Density of insert	14900 kg/m^3
Specific heat of insert	208 J/kg.K
Thermal conductivity of tool holder	42.6 W/m.K
Initial temperature	18°C

Table 4 — Water properties Cooling fluid properties

Specific heat	4182 J/kg K
Density	1000 kg/m³
Viscosity	0.001 kg/m s
Thermal conductivity	0.6 W/m K

were recorded. At a low cutting speed in the dry machining operation, surface quality was higher with the internal cooling method. However, as the cutting speed increases, the quality of the surface improves accordingly. The developed system provided up to 12% better quality than the surface quality obtained in dry machining. The tool-chip interface temperature and the surface quality showed significant improvements after applying internal cooling. Figure 11 shows surface roughness comparisons at the dry and internally cooled conditions for various cutting speeds. The maximum levels of both coolant flow rate and cutting speed resulted in the highest surface quality.

Finite element simulation of cutting temperatures

Finite element analysis (FEA) was used to develop a 3-D temperature simulation model based on the projected temperature over the tool-chip contact region. In order to achieve more realistic and accurate simulation results, the model was designed using the actual geometry of the cutting tool and tool holder. The transient thermal analysis was performed using an ANSYS commercial finite element code. In the analysis, triangular elements were used to construct the tool holder. The number of elements is 79237 and the node number is 460018.

A typical simulation for a cutting tool for heat flow $Q = 23$ W showed that the maximum temperature of 607°C near the heat source was decreased to 545°C with the internal cooling method (inlet velocity = 1.6 m/s). The cooling water pipeline is shown in Fig. 12. FEA model input values for the cutting tool are given in Table 3.

The heat flux was applied over the tool-chip contact area on the cutting insert. The boundary conditions applied to the computational fluid dynamics model are given in Fig. 13. The required cooling fluid properties are given in Table 4.

The temperatures obtained from one of the experimental tests were measured as 565°C on the tool-chip interface and 72°C on the tool at a cutting depth 0.5 mm, a cutting speed of 113 m/min and a feed rate of 0.08 mm/rev under dry conditions. When the internally cooled cutting tool was applied at an inlet velocity of 0.8 m/s, it was possible to reduce the temperature at the tool-chip interface to 520°C and the temperature of the tool to 58°C.

Using FEA, the temperature changes were simulated in order to verify and confirm the experimental results. The FEA result showed that by using the internally cooled cutting tool, the conventional tool-chip interface temperature recorded as 559°C could be reduced to 521°C and the tool temperature to 57°C. The simulated temperature difference between the dry and internally cooled conditions was approximately 38°C. Figure 14 illustrates the simulated tool holder temperature distribution under dry and internally cooled conditions. The experimental and simulated temperature distribution results showed good agreement.

Conclusions

This paper presents a new cooling method in turning using an internally cooled tool holder. It consists of a tool holder with cooling fluid circulating inside a closed internal cooling system. A prototype that facilitates the cooling from inside the tool holder was specifically designed and manufactured. Using a conventional lathe, a series of cutting trials was carried out in order to investigate the practicality and effectiveness of the proposed internally cooled tool holder. It was concluded that, in the machining process, application of this internal cooling method exhibited superior long-term efficiency. The major findings of this work can be summarized as follows:

(i) The maximum temperature on the tool at the tool-chip interface was observed to decrease from 607°C to 545°C with the internal cooling method. This clearly indicated that internal cooling can sufficiently reduce the cutting temperature and enable the cutting tool to work while avoiding the critical cutting temperature by controlling it during the process, which is vitally important in extending tool life during the machining of hard materials.

(ii) At a low cutting speed in the dry cutting operation, surface quality was higher than with

the internal cooling. However, as the cutting speed increases, the surface quality improves. The developed system provided up to 12% better surface quality than the quality obtained in dry machining.

(iii) According to the experimental results, it was possible to extend tool life up to 15% by using the internal cooling method, while at the same time avoiding environmental hazards and health problems.

(iv) In the analysis of the results, it was observed that the velocity of the fluid had a significant effect on the cooling efficiency. For all conditions, when the inlet velocity was more than 1.0 m/s, the tool temperature decreased slightly. It was found that the temperature differences between inlet and outlet decreased with the increase in the flow rate.

(v) In dry machining, the tool temperature can be reduced by up to 11% using a cooled tool holder, thus enabling the tool to perform below the critical diffusion wear-activated temperature for carbide tools, even in the most aggressive machining situations.

(vi) The internal cooling structure can provide an eco-friendly and cost-effective alternative to cutting fluids.

Acknowledgements

References

1   Sanchez L E A, Scalon V L & Abreu G G C, Cleaner Machining through a toolholder with internal cooling, *3rd Int Workshop Advances in Cleaner Production,* Sao Paulo, Brazil, 8-20 May 2011.

2   Acun I & Aslantaş K, *Int J Adv Manuf Technol*, 54 (2011) 899-910.

3   Longbottom J M & Lanham J D, *Int J Aircraft Eng Aerospace Technol*, 77(2) (2005) 122-130.

4   Vicentin G C, Sanchez L E A, Scalon V L & Abreu G G C, *Clean Technol Environ Policy,* 13 (2011) 831-840.

5   Sharma S V, Dogra M & Suri N M, *Int J Mach Tools Manuf,* 49 (2009) 435-453.

6   Kara F, Aslantaş K & Çiçek A, *Appl Soft Comput*, 38 (2016) 64-74.

7   Sata T & Takeuchi Y, *Ann CIRP*, 30 (1981) 445-449.

8   Chiou R Y, Lu L, Chen J S J & North M T, *Int J Adv Manufact Technol*, 31 (2007) 905-914.

9   Diniz A E & Micaroni R, *Int J Mach Tools Manuf*, 42 (2002) 899-904.

10   Klocke F & Eisenblatter G, *Ann CIRP*, 46 (1997) 519-526.

11   Sun X, Bateman R, Cheng K & Ghani C S, *J Eng Manuf Part B*, 226(4) (2012) 585-591.

12   Rozzi J C, Sanders J K & Chen W, *J Heat Transfer*, 133 (2011) 1-10.

13   Hong S Y & Broomer M, *Clean Prod Processes*, 1 (2000) 157-166.

14   Isik Y, *Stroj Vest-J Mech Eng*, 56 (2010) 252-262.

15   Ramana M V, Srinivasulu K & Rao, M K G, *Int J Innov Technol Creat Eng,* 1 (2011) 10-21.

16   Marksberry P W & Jawahir I S, *Int J Mach Tools Manuf*, 48 (2008) 878-886.

17   Dhar N R, Paul S & Chattopadhyay A B, *Wear*, 249 (2002) 2932-2942.

18   Sreejith P S, Ngoi & B K A, *J Mater Process Technol*, 101 (2000) 287-291.

19   Shu S, Cheng K, Ding H, Chen S, *J Manuf Sci Eng*, 135(6) (2013) MANU-13-1204

20   Zhao H, Barber G C & Zou Q, *Wear*, 253 (2002) 957-962.

21   Ghani C S, *Design and analysis of the internally cooled smart cutting tools with the applications to adaptive machining*, Ph. D. thesis, Brunel University, UK, 2013.

22   Kus A, Isik Y, Cakir M C, Coskun S & Ozdemir K, *Sensor*, 15 (2015) 1274-1291.