Strojniški vestnik - Journal of Mechanical Engineering 55(2009)11, 685-694
UDC 621.9.01

Paper received: 09.07.2009
Paper accepted: 20.11.2009

High Pressure Cooling in the Machining of Hard-to-Machine Materials

Davorin Kramar [*]- Janez Kopač
University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia

This paper investigates the application of high-pressure cooling (HPC) assistance in the rough turning of two different hard-to-machine materials, namely hard-chromed and surface hardened C45E and Inconel 718 with coated carbide tools. The region of operability – technology windows, which sets the boundaries of the process parameters, has been experimentally determined using the tool–material pair (TMP) methodology. The capabilities of different hard turning procedures are compared by means of chip breakability, cooling efficiency, temperatures in cutting zone, tool wear and cutting forces. All machining experiments were performed under conventional cutting speeds.

Keywords: high pressure cooling, machinability, technological windows, tool wear

0 INTRODUCTION

High-pressure jets (HPJs) have been in use since 1900. In the USA, such jets were introduced in mining applications to wash out valuable materials like gold by excavating soft gold-bearing rocks. In the fifties Pigott [1] was the first author to discuss the use of HPJ assisted machining of steel with high speed steel tools. The cutting liquid was injected at a pressure of 2.76 MPa directly at the clearance of the tool. He found that the temperature dropped by 24 °C and that tool life increased by up to eight times. In addition, it was found that the use of a high speed jet led to an improved surface roughness compared to the conventional cooling at low pressure and high flow rate. In the late 1960's, R. Franz from the University of Michigan examined the cutting of wood with high velocity jets. His idea stems from the way steam leaks were detected in invisible spots. A broom was moved through locations where a leak was expected. While examining the damage done to the broom, the idea that a jet of high velocity water could also cut materials arose. This idea led to the first industrial water-jet (WJ) cutting application [2]. In the 1970’s the first hydraulic intensifier pump which reaches the pressures up to 400 MPa was developed and since then high pressure jets are applied in nearly all areas of modern industry. Generally, HPJs are used for industrial cleaning, surface preparation, paint and coating stripping, concrete hydrodemolition, rock fragmentation, assisted mining operations, rock and soil drilling and stabilization, decontamination, demolition, material recycling, and manufacturing operations. In the area of manufacturing, the jet-technique is used for material cutting by plain WJs (e.g., plastics, thin metal sheets, textiles, foam), deburring by plain WJs, surface peening by plain WJs, different abrasive waterjet (AWJ) cutting and machining techniques, and conventional machining with HPJ assistance. This paper focuses on the last application mentioned above.

Machining performance can be improved dramatically by controlling the tool–chip interfacial temperature rise and frictional effects using a coolant. A flood of fluid directed over the back of the chip is the most common method of applying the cutting fluid. The advantages of this use, however, have been called into question lately due to the negative effects on product cost, the environment and human health. Klocke and Eisenblätter [3] reported that 15% of the total cutting cost is due to the use of cutting fluids, while the cost of tooling is only 4%. On the other hand, new techniques, materials and tools have shown that dry machining is preferable to the use of a coolant. At present, high speed cutting technology is the most promising approach to increase both, the efficiency and precision of machining processes. However, there are new alloys that are particularly difficult for machining e.g. hardened steels used for moulds, Cr-Co alloys used for prosthesis, Ti-based and Ni-based alloys used in gas turbines and in the aerospace

---

[*]Corr. Author's Address: Faculty of Mechanical Engineering, University of Ljubljana
Askerceva 6, 1000 Ljubljana, Slovenia, davorin.kramar@fs.uni-lj.si

industry, where high speed cutting technologies are encountering serious difficulties as they cannot be effectively cut without cooling, even with the latest coatings [4]. One approach to enhance the machining performance in the cutting of such materials is hot machining. Kitagawa and Meakawa [5] found that machining by softening the workpiece is a more effective way than strengthening the tool. The most important achievement in hot machining is to obtain longer tool life and better surface finish. But the technique is not economical and practical. Microcooling with oil–air mixtures also called near-dry cutting [6] and cryo-cooling [7] have also been introduced. Both techniques contribute to the reduction of cutting fluid consumption.

Machining with high-pressure cooling (HPC) is also beginning to be established as a method for a substantial increase of removal rate and productivity in the metal cutting industry. Cooling with high pressures in turning operations is an effective method for providing higher productivity, reducing temperature in the cutting zone and improving chip control depending on the pressure and flow rate of the fluid jet. Cutting fluids have a direct influence on the environment and manufacturing economics. By abandoning conventional cooling and using the technologies of dry machining or HPC, the cost related to the usage of cutting fluids can be reduced. Besides an improvement in the efficiency of the machining process, those principles can contribute to the environment concerns.

The machining of ‘hard-to-machine’ materials with coated carbide tools, conventional turning parameters and conventional cooling, usually results in significant problems concerning extremely long chips and severe adhesion wear mechanisms. By applying HPC at reduced flow rates, the friction and the heat induced in tool-chip interface can be reduced. Based on this technology turning of hard-to-machine materials with conventional cutting speeds and low cost coated carbide tools can be performed.

The aim of this investigation is to compare the capabilities of dry, conventional and HPC turning of hard-to-machine materials. All investigations are performed with conventional cutting speeds and the use of coated carbide tools. The performances of different cutting conditions are compared on the basis of chip breakability, technological windows which yield particular operational ranges, cooling efficiency, tool wear, cutting forces and manufacturing costs.

1 HIGH PRESSURE COOLING (HPC)

In machining, the chip formation is largely influenced by the heat and friction generated in the contact zone between the rake face of the tool and the machined surface material. In the turning of hard-to-machine materials, the thermal influence can lead to high temperatures and structural alterations of the workpiece material, causing the change of the material’s mechanical properties. The thermal impact mainly depends on the cooling and lubrication capability as well as the maximum temperature reached in the cutting zone. Conventional cooling is not efficient enough to prevent extreme thermal conditions in the cutting zone especially when cutting advanced materials. Compared to the conventional cooling, the idea of HPC is to inject a high pressure jet of emulsion in the cutting zone. The lathe should be fitted with high pressure equipment. This involves a high pressure pump, high pressure tubing, and an outlet nozzle fixed beside a tool holder. The pump is supplied with filtered water or emulsion.

The jet can be applied in two ways:

- With an external nozzle (Fig. 1): The jet is injected directly in between the rake face and the chip or can be directed to the gap between the flank face and the workpiece.
- Through internal channels: The fluid is injected through the tool using small holes in the insert.

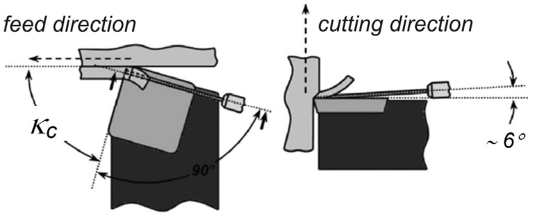


Fig. 1. *Illustration of the high-pressure cooling set-up*

The supply of high pressure jet between the rake face and the chip decreases the length of their contact. On the other hand, the cutting zone can be reached by injecting the coolant below the flank face of the tool. The following procedure is the most efficient in reducing the temperature in the cutting zone, but has no influence on chip breakability. In this investigation the realisation shown in Fig. 1 has been used. HPC is applied on the rake face through an external nozzle, which is relatively easy to set on the conventional lathe.

Öjmertz and Oskarson [8] carried out machining experiments on Inconel with HPC under pressure in the range of 80 to 380 MPa. The HPJ was applied directly into the tool-chip interface. It was found that cooling introduced by the HPC enhanced the surface finish quality with reduced burr. At high pressure, the jet was observed to penetrate deeper into the tool-chip interface, which reduced the fracture toughness of the chip material, resulting in effective chip breaking. The test results, however, indicated an accelerated notch wear rate on SiC-whiskers reinforced ceramic tools.

There were many other investigations carried out at the Chalmers University of Technology on HPJ assisted turning of steel [9] to [13]. In these investigations an extensive analysis of the possibilities for controlling the chip formation was reported. In [9] to [11] it is showed how to control the chip curl radius, chip-flow direction and chip breakage by setting the appropriate jet parameters. A significant temperature reduction in the cutting zone and surface roughness due to the use of HPC is reported in [12] and [13]. The authors concluded that material properties determine whether high pressure or high flow have to be used to achieve the best cooling effect in the turning of soft stage steels with carbide tools.

In extensive investigations by Ezugwu et al. performed in the last decade [14] to [16], a pressurized water-based coolant was directed into the tool-chip interface from an external nozzle with the pressure up to 20 MPa. The credibility of this coolant delivery technique has been thoroughly investigated and performed on hard-to-machine nickel-based and titanium alloys. Ezugwu and Bonney [14] confirmed the feasibility of using HPC in the rough turning of Inconel 718 with coated carbide tools. The investigation showed the HPC benefits related to the decrease of tool-chip contact length, which could contribute to the decrease of temperature. In the next study Ezugwu et al. [15] assessed the whisker reinforced ceramic tool life during the machining of Inconel 718 at different cutting speeds and under different coolant pressures. It was proved that at all cutting speeds, tool life increased when the coolant pressure of up to 15 MPa was employed. However, when pressure was increased from 15 to 20.3 MPa, tool life decreased rapidly due to excessive notching at the depth of cut region. The authors attributed notch wear to the erosion of the ceramic tool, caused by the HPC. Ezugwu et al. [16] also assessed the tool life of uncoated carbide and CBN tools when turning Ti-6Al-4V alloy using conventional and HPC. When using CBN tools, tool life was increasing with coolant pressure throughout the tested pressure range. When uncoated carbide tool was used, tool life was increasing with the coolant pressure throughout the tested pressure range, from the conventional application to 15 MPa. The opposite trend was observed when pressure was further increased to 20.3 MPa. The authors attributed this decrease to the critical boiling action of the coolant at the tool edge, since it was possible to sweep the tool surface faster with the higher jet speed, thus lowering the rate of boiling and cutting down the heat transfer.

The analysis of existing work in the discussed machining area revealed a technological gap. The hard turning of steels and Inconel with coated carbide tools at conventional cutting speeds is filling this gap. This machining is attainable by supplying a vegetable oil-based emulsion as a coolant at reduced flow rates and pressures larger than 50 MPa.

2 EXPERIMENTAL WORK

2.1 Experimental Set-up and Equipment

In the experiments hard chromium platted and surface induction hardened steel C45E (AISI 1045) and nickel alloy - Inconel 718 were tested. Both materials are known to induce chip control problems, which makes them suitable for HPC machining. The depth of the hardened surface layer for C45E was between 1.5 and 1.8 mm with a hardness of 58 HRc. The cutting tool inserts used in the experiments with C45E were coated carbide cutting tools – SANDVIK SNMA 120408 with Al_2O_3 coating, while Inconel with hardness 36 to 38 HRc was machined with coated carbide cutting tools – SANDVIK SNMG 120408-23 with TiAlN coating. The inserts for C45E machining were flat-faced, while inserts for Inconel had positive geometry with rake angle of

13°. The tests were conducted in longitudinal turning on a conventional lathe, equipped with a high pressure plunger pump of 200 MPa pressure and 8 l/min flow capacity. Standard sapphire orifices of 0.25, 0.3 and 0.4 mm diameter, commonly used in waterjet cutting applications are mounted with a custom made tool clamping device that enables accurate coolant jet adjustments.

A 0.3 mm diameter orifice was used for C45E cutting, while 0.25 and 0.4 mm were used for Inconel cutting. The cooling lubricant jet was directed to the cutting edge at a low angle of 5º with the rake face at the distance of 22 mm. The coolant was a 5.5% emulsion based on vegetable oil and water without the presence of chlorine. The cutting tool was mounted on the Kistler multi-component dynamometer, which measures three components of the cutting force. The measurement chain further includes a charge amplifier, a spectrum analyzer and a PC for data acquisition and analysis.

Tool wear measurements and images were acquired with a CCD camera mounted on a Mitutoyo TM microscope aided with imaging software. Surface roughness was measured with a stylus type instrument Mitutoyo - Surftest SJ-301.

2.2 Experimental Sequence

Machining experiments were conducted in dry, conventional and HPC conditions. The experimental sequence consisted of three steps:

1. In the first step, screening experiments were conducted in order to determine coolant pressures that yield adequate chip breakability and cooling capability. Within this experimental step the influence of coolant pressure on the cutting forces was analysed.
2. In the second step, technological windows for all three cooling conditions were determined. The technological window sets the boundaries of the process cutting speed-feed rate operational area, and is the base for technological database construction [17]. The methodology involved measurements of the cutting forces and an analysis of the generated chips and is based on the French national standard NF E 66-520-6 [18]. This experimental step was required because no machining data was available for turning of both materials with coated carbide tools. Within this experimental step the depth of cut and the coolant condition were kept constant.
3. In the third step, experiments were performed with the cutting speed and the feed rate belonging to the cross-section of overlapped technological windows for particular cooling condition determined in the previous step. By measuring the tool wear the assessment and comparison of cooling capability was conducted. Within this experimental step the depth of cut was also kept constant.

3 RESULTS AND DISCUSSION

3.1 Initial Experiments

Within the initial experiments on hardened steel **C45E** different pressures were applied while the cutting speed, v_c = 98.5 mm/min, feed rate, f = 0.25 mm/rev, and depth of cut, a_p = 2mm, were kept constant. The nozzle for all experiments was 0.3 mm. At pressures 10 and 30 MPa a relatively good breakability of chips was observed. However, the lack of cooling was noticed because the chips were significantly blackened, hence burned as can be seen in Fig. 2. The results have shown that dry cutting conditions are not appropriate for this material at such depth of cut. Insufficient cooling is related to a low coolant flow rate at such pressures, with the amounts of 0.4 l/min at 10 MPa and 0.7 l/min at 30 MPa. At pressures higher than 70 MPa, good breakability of chips as well as suitable cooling was observed.

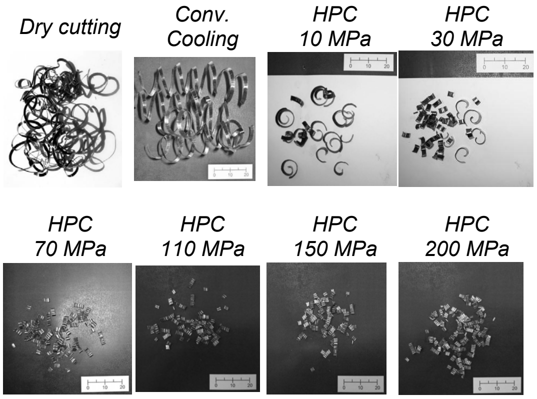


Fig. 2. *Chip forms regarding the cooling conditions and coolant pressure for C45E*

In the initial experiments the influence of the coolant pressure on the cutting forces was analysed. The feed and radial force decreased as soon as the HPC was applied but no real trend could be noticed with the increase of the pressure (Figs. 3 and 4). In the case of the main cutting force it was more difficult to verify a significant trend, whereas the small variations observed can be considered to be within the margin of measurement error.

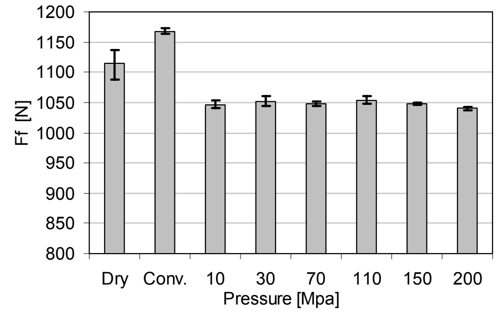


Fig. 3. *The influence of the coolant pressure on the feed force for C45E*

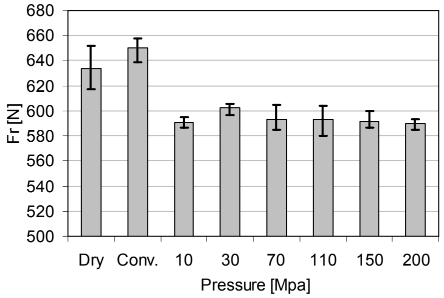


Fig. 4. *The influence of the coolant pressure on the radial force for C45E*

For the subsequent experimental steps in HPC machining of hardened steel C45E, the pressure of 110 MPa was chosen. This pressure at 0.3 mm nozzle yields a flow of approximately 1.4 l/min.

The pressure for HPC machining of **Inconel 718** was chosen with regard to the pump capacity with the aim to analyse the influence of coolant flow on cutting performance. Two different nozzles were used: 0.25 mm and 0.4 mm. The highest pressure achieved with large nozzle was 130 MPa. The coolant flow at this setting is approximately 2.6 l/min. The lowest flow rate was defined as 10 times lower than in case of conventional cooling at 0.6 l/min. This flow rate could be achieved with a smaller nozzle at pressure of 50 MPa. Within the initial experiments on Inconel 718 these two pressures (50 and 130 MPa) were applied while the cutting speed, v_c = 50 mm/min, feed rate, f = 0.25 mm/rev, and depth of cut, a_p = 2mm, were kept constant. A relatively good breakability of chips was observed in all cooling conditions. The colour of chips was brightly metal in all cases except in dry conditions as can be seen in Fig. 5. This indicates that in all cases sufficient cooling was applied. In dry cutting of Inconel, burned, golden colour chips were formed regardless of the cutting parameters. Besides, very high temperature in the cutting zone was observed. The chips turned red during cutting and the insert was worn immediately. The results have shown that dry cutting conditions are also not appropriate for this material at such depth of cut.

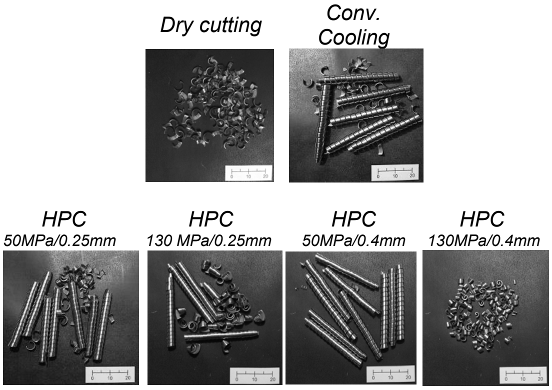


Fig. 5. *Chip forms regarding the cooling conditions in Inconel 718 turning (v_c = 50 mm/min, f = 0.25 mm/rev, a_p = 2 mm)*

3.2 Technological Windows

The procedure for operational regions – technological window definition for both materials is described in detail in [19].

*Hard chromium platted and surface induction hardened steel **C45E***

According to the maximum rotation speed limitation of the spindle, cutting speeds higher than 200 m/min were not tested and the upper limit was fixed to 158 m/min for safety reasons. Fig. 6 shows operational areas for TMP for the.

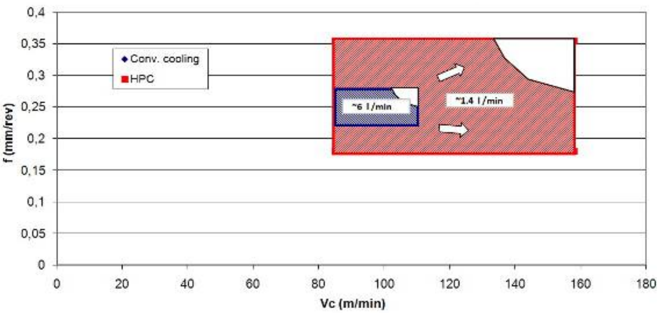


Fig. 6. *Technological window for TMP in HPC and conventional cooling of hardened steel C45E*

case of conventional cooling and HPC conditions. An extension of the operational area for both cutting parameters is achieved with HPC. More specifically, a 45% increase in the maximum achievable cutting speed and approximately 25% increase in the maximum achievable feed rate are shown

Inconel 718

In HPC of Inconel two different orifice diameters were tested, namely 0.25 and 0.4 mm. The pressures were also set on two levels, 50 and 130 MPa. These settings gave 4 different flows of coolant. TMP methodology was performed for all 4 conditions and the influences of cooling on the cutting capability were analysed. At pressure 50 MPa no evident enlargement of the technological window in comparison to conventional flooding was achieved when smaller nozzle was applied (Fig. 7). This is probably because of a low contribution of HPC in chips breakability and insufficient cooling with such low jet momentum. The flow rate of coolant in this pressure/nozzle (50 MPa/0.25 mm) combination was only 0.6 l/min. At pressure of 130 MPa with the same nozzle, better results were achieved. The technological window was enlarged on the side of lower cutting speeds and lower feed rates. The results with a considerably better productivity and flexibility were achieved with a larger nozzle (0.4 mm). Even with lower pressure level the cutting performance was increased, which is shown with the technological window in Fig. 7. Both, higher and lower cutting speeds and feed rates compared to conventional cooling can be used with such a nozzle for both of the applied high pressures. Fig. 7 also shows the consumption of coolant at different cooling conditions. The highest improvement in the cutting performance in the connection with the lowest coolant consumption is achieved with a larger nozzle and lower pressure. In this case almost a quarter of cutting fluid is used compared to conventional cooling.

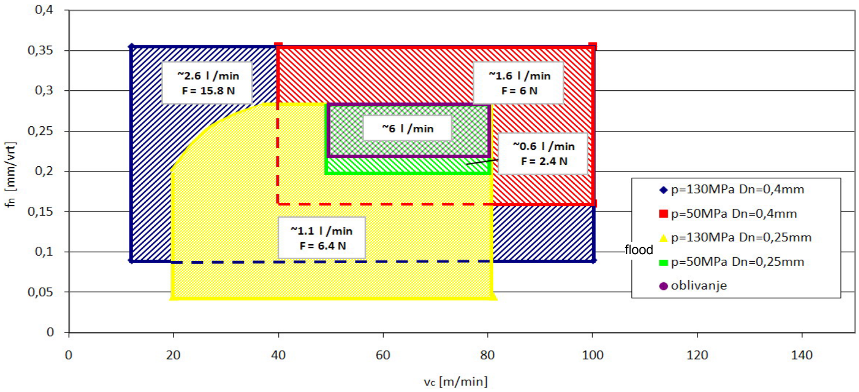


Fig. 7. *Technological windows for four HPC cases and for conventional cooling with a consumption of coolant (Inconel 718)*

3.3 Machinability Tests – Cooling Capability

*Hard chromium platted and surface induction hardened steel **C45E***

The capability of cooling can be characterised by tool life and tool wear [20]. In order to assess and compare the capability of cooling conditions, experiments were carried out within the common cross-section of overlapped technological windows for a particular cooling condition (Fig. 6). The following cutting conditions were employed in this step of investigation:

- Depth of cut a_p = 2 mm,
- Feed rate f = 0.25 mm/rev,
- Cutting speed v_c = 98.5 m/min,
- Workpiece diameter d = 30 mm,
- Cutting fluid concentration c = 5.5%.

Crater wear changes the effective rake face angle and leads to a changing cutting behaviour. Excessive crater wear weakens the tool just behind the cutting edge. As a result, a sudden break down of the cutting edge can occur. The flank wear occurs as a flattened area on the cutting tool flank face. The width of flank wear, referred to as the flank wear land width *VB*, is traditionally considered a good indicator of the state of the cutting tool. An increase in *VB* leads to increased friction between the cutting tool and the workpiece. Consequently, a higher specific cutting force and more heat are generated. It was discovered that a flank wear land width of *VB* = 0.1 mm does not lead to workpiece damage.

In conventional cooling the distribution of the flank wear *VB* proved very uniform. It can be seen that besides flank wear also wear on the rake face has occurred in the shape of crater wear *KBmax*. The flank wear of *VB* = 0.1 mm has occurred in less then 2 minutes (Fig. 8). In HPC condition the distribution of the wear along the flank face was also quite uniform, however some marks of notch wear at the depth of the cut line can also be noticed. Crater wear was also present on the rake face. The changes in the specific cutting force and roughness were noticed as a consequence of the increased tool wear.

Fig. 8 shows the tool flank wear trend in conventional cooling and HPC. For the selected criteria *VB* = 0.1 mm, tool life in the case of HPC was about 10 minutes, which is approximately 5 times longer than in the case of conventional flooding. It should be pointed out that the consumption of cutting fluid in the case of HPC is more than 4 times lower as in the case of conventional cooling.

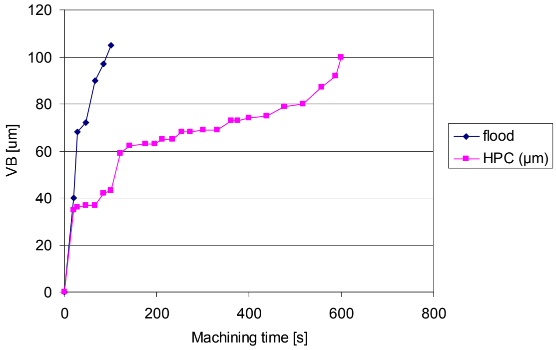
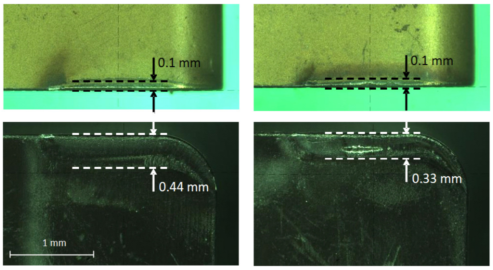


Fig. 8. *Tool wear development in conventional and HPC for C45E*

The effect of HPC on the tool rake face wear can also be observed in Fig. 10 where both tools for conventional and HPC conditions at *VB* = 0.1 mm are compared. The contact length in HPC conditions is approximately one third shorter than in the case of conventional cooling.



a) b)

Fig. 9. *Comparison of flank wear at VB = 0.1 mm and contact length in a) conventional, b) HPC for C45E*

Inconel 718

Similar tests as in case of steel C45E were performed on Inconel 718. In order to assess and compare the capability of cooling conditions, experiments were carried out with HPC pressure set on 50 MPa, and nozzle of 0.3 mm diameter was used. The following cutting conditions were employed in this step of investigation:

- Depth of cut $a_p = 2$ mm,
- Feed rate $f = 0.25$ mm/rev,
- Cutting speed $v_c = 55$ m/min,
- Workpiece diameter $d = 140$ mm,
- Cutting fluid concentration $c = 5.5\%$.

Tool flank wear development for both cooling conditions is shown in Fig. 10.

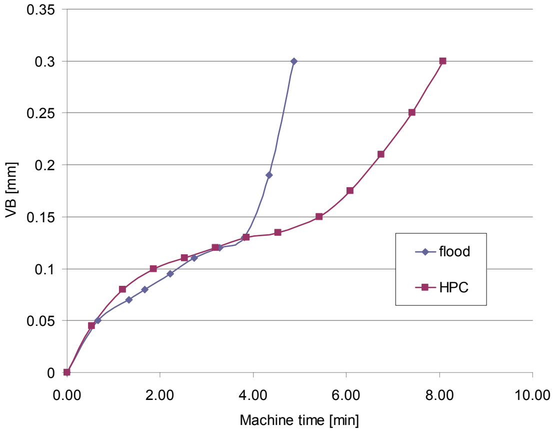


Fig. 10. *Tool wear development in conventional and HPC for Inconel 718*

In conventional cooling, for the chosen tool wear criteria of *VB* = 0.3 mm, the tool is rejected within 4.5 min. In HPC tool life was more than 8 min. A sudden increase of tool wear is typical for flooding condition, while in HPC a more uniform increase was noticed. The changes in the specific cutting force and roughness were noticed as a consequence of the increasing tool wear again.

In case of Inconel cutting also temperature below the cutting zone was measured. A thermocouple was directly embedded in the insert to reach this aim. The main drawback of this measurement technique is that it does not reflect the maximum temperature and its exact location and hence cannot be used to measure the cutting temperature as the average overall temperature. The conducted measurement is thus qualitative, employed to assess the heat transmitted into the tool through a fixed reference point.

The efficiency of HPC in limiting the heat transmitted to the tool can be illustrated by the online measurements shown in Fig. 11. It can be stated that a 30% decrease in tool temperature compared to conventional cooling is achievable with a 450% reduction in coolant flow. The thermal advance is substantial compared to dry cutting with an approximate decrease of tool temperature by 70%. In consideration of the pressures used, the high speeds of the jet are governing a high convective heat transfer through the turbulent behaviour of the fluid. These attributes to the fluid increased heat dissipation capabilities, which prevents the cutting tool from excessive heating.

4 CONCLUSIONS

The presented research is based on experimental observation of two hard-to-machine materials, in turning processes, where the main difference is in the utilized cooling. In the first case dry cutting is performed. In the second and the third case conventional and HPC methods are employed. The experimental work has proved that the turning of both materials, chromium platted and surface induction hardened steel C45E

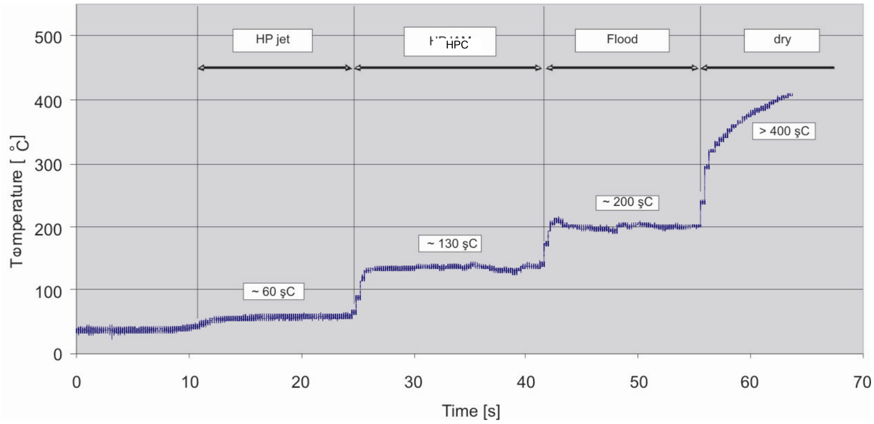


Fig. 11. *Comparison in temperature measurements between three cooling conditions*

and Inconel 718 with coated carbide tools at conventional cutting speeds is not possible in dry cutting conditions. The process capabilities of conventional and HPC methods are compared with respect to chip breakability and cutting forces. Both processes are characterized with technological windows that yield the operational area according to the employed tool-material pair. The major concluding remarks related to the HPC precedence over conventional cooling in the turning of both hard-to-machine materials with coated carbide tools are:

For chromium platted and surface induction hardened steel ***C45E***:

- An extension of the operational area for a given tool-material pair. More specific, approximately 35% increase in both the maximum achievable cutting speed and the maximum achievable feed rate were shown.
- A significant increase in chip breakability.
- A five times increase in tool life (VB=0.1 mm), from 2 to 10 minutes was achieved.
- All machining advantages mentioned above were achieved with a reduction of coolant consumption by four times.

For ***Inconel 718***:

- An extension of the operational area for a given tool-material pair strongly depends on nozzle diameter and pressure applied. More specifically, with a smaller nozzle (Dn = 0.25 mm) and lower pressure (p = 50 MPa) no significant improvement compared to conventional cooling was achieved. With the same nozzle but at higher pressure (p = 130 MPa) the technological window was enlarged on the side of lower cutting speeds and lower feed rates. Considerably higher performance was achieved with larger nozzle (Dn = 0.4 mm). More than 20% increase in the maximum achievable cutting speed and almost 30% increase in the maximum achievable feed rate at both pressures were shown.
- A significant increase in chip breakability.
- Almost double tool life (VB = 0.3 mm), from 4.5 minutes to more than 8 minutes was achieved.
- Temperature measurements exposed a major improvement compared to dry cutting and conventional cooling.
- All machining advantages mentioned above were achieved with a reduction of coolant consumption. The best results considering higher productivity and lower coolant consumption were attained with the combination of a larger nozzle (Dn = 0.4 mm) and lower pressure (p = 50 MPa).

In the future, parameter effects on the surface integrity should be thoroughly investigated in order to identify advantages related to improved fatigue behaviour of the machined part. Moreover, experiments should be carried out to investigate the jet tribological influence on machining performance.

5 ACKNOWLEDGMENT

The authors would like to acknowledge the support of Hammelmann Maschinenfabrik GmbH for providing the high-pressure pump, which enabled this study to be carried out. This research was conducted within the CORNET High Performance Manufacturing integrated project, under the 6th Framework Programme for Research and Technological Development, funded by the European Union.

6 REFERENCES

[1] Pigott, R.J.S. Method of applying cutting liquids, *US Patent* 2,653, 1953.

[2] Summers, D.A. Waterjetting Technology, *Chapman & Hall*, 1995, ISBN 0-419-19660-9.

[3] Klocke, F., Eisenblätter, G. Dry cutting, *Annals of the CIRP*, vol. 46, no. 2, 1997, p. 519-526.

[4] Outeiro, J.C., Pina, J.C., M'saoubi, R., Pušavec, F., Jawahir, I.S. Analysis of residual stresses induced by dry turning of difficult-to-machine materials, *Annals of CIRP*, vol. 57, no. 1, 2008, p. 77-80.

[5] Kitagawa, T., Maekawa, K. Plasma hot machining for new engineering materials, *Wear*, vol. 139, 1990, p. 251–267.

[6] Weinert, K., Inasaki, I., Sutherland, J.W., Wakabayashi, T. Dry Machining and Minimum Quantity Lubrication, *Annals of CIRP*, vol. 53, no. 2, 2004, p. 511-537.

[7] Pusavec, F., Krajnik, P., Kopač, J. Transition to sustainable production – part I: Application on Machining Technologies,

Journal of Cleaner Production, 2009, In press.

[8] Öjmertz, K.M.C., Oskarson, H.B. Wear on SiC-Whiskers Reinforced Ceramic Inserts When Cutting Inconel With Waterjet Assistance, *Tribology Transactions*, vol. 42, no. 3, 1999, p. 471-478.

[9] Crafoord, R., Kaminski, J., Lagerberg, S., Ljungkrona, O., Wretland, A. Chip control in tube turning using a high-pressure water jet, *Proc. Instn Mech. Engrs, Part B, Journal of Engineering Manufacture*, vol. 213 (B8), 1999, p. 761-767.

[10] Kaminski, J., Alvelid, B. Temperature reduction in the cutting zone in water-jet assisted turning, *Jour. of Mater. Proc. Tech.*, vol. 106, no. 1-3, 2000, p. 68-73.

[11] Dahlman, P. Comparing the temperature reduction in high-pressure jet-assisted turning using high pressure versus high flow, *Journal of Engineering Manufacture*, vol. 216, no. 4, 2002, p. 467-473.

[12] Dahlman, P., Escursell, M. High-pressure jet-assisted cooling: a new possibility for near net shape turning of decarburized steel, *Inter. Jour. of Machine Tools and Manufacture*, vol. 44, no. 1, 2004 p. 109-115.

[13] Kaminski, J., Ljungkrona, O., Crafoord, R. and Lagerberg, S. Control of chip flow direction in high pressure water jet assisted orthogonal tube turning, *Proc. Instn Mech. Engrs, Part B, Journal of Engin. Manuf.*, vol. 214, (B7), 2000, p. 529-534.

[14] Ezugwu, E.O., Bonney, J. Effect of high-pressure coolant supply when machining nickel-base, Inconel 718, alloy with coated carbide tools, *Jour. of Mater. Proc. Tech.*, vol. 153-154, no.10, 2004, p. 1045-1050.

[15] Ezugwu, E.O., Bonney, J., Fadare, D.A., Sales, W. F. Machining nickel-base, Inconel 718, alloy with ceramic tools under conditions with various coolant supply pressures, *Jour. of Mater. Proc. Tech.*, vol. 162–163, 2005, p. 68-73.

[16] Ezugwu, E.O., Da Silva, R.B., Bonney J., Machado, Á.R. Evaluation of the performance of CBN tools when turning Ti–6Al–4V alloy with high pressure coolant supplies, *Int. Journal of Machine Tool and Manufacture*, vol. 45, no. 9, 2005, p. 1009-1014.

[17] Čuš, F., Muršec, B. Databases for technological information systems. *J. mater. process. technol.*, vol.157/158, 2004, p. 75-81.

[18] AFNOR Standard NF E 66-520, Couple outil—matière *Domaine de fonctionnement des outils coupants*, vol. 1–6, 1994.

[19] Kramar, D., Kopač, J. High performance manufacturing aspects of hard-to-machine materials, *Advances in Production Engineering & Management*, vol. 4, no. 1-2, 2009, p. 3-14.

[20] Župerl, U., Čuš, F. Machining process optimization by colony based cooperative search technique, *Stroj. vestn.- Jour. of Mech. Engin.*, vol. 54, no. 11, 2008, p. 751-758.