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HIGH PERFORMANCE MANUFACTURING ASPECT OF HARD-TO-MACHINE MATERIALS

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Abstract:
An experimental study has been performed to investigate the capabilities of dry, conventional and high pressure jet assisted turning of two different hard-to-machine materials, namely hard-chromed and surface hardened Ck45 and Inconel 718. The capabilities of different hard turning procedures are compared by means of chip breakability, technological windows, cooling lubrication efficiency, and cutting forces. All machining experiments are performed under conventional cutting speeds using coated carbide tools.

Key Words: High pressure cooling lubrication, Machinability, Technological windows, Chip breakability

1. INTRODUCTION

High performance manufacturing is an inclusive term incorporating many existing theories and approaches on productivity and waste reduction. It is an approach based on a commitment to continuous improvement and enhanced competitiveness. Manufacturers are urged to use step in a process that will guide them toward sources of information and expertise that will help them increase their productivity, competitiveness and success.

The performance of cutting operations is measured with the machining cycle time, surface quality and tolerance integrity of the workpiece. The selection of tool geometry and material, lubricants, and cutting conditions are dependent on the process, machine tool, material, and the interaction between them.

Metal cutting is a process of material removal in which the loss of material is caused by effecting a relative motion between tool and workpiece. It involves complex thermo mechanical phenomena, such as high strain rate in the primary shear zone, frictional contact interaction between the chip and tool in the secondary shear zone, and elevated temperature in the chip induced by mechanical energy dissipation. The greater the energy consumption, the more severe are the thermal/frictional conditions, making metal cutting process more and more inefficient in terms of tool life, dimensional accuracy and material removal rate. Consequently, cutting performance can be improved enormously by controlling the tool–chip interfacial temperature rise and frictional effects using a coolant/lubricant. 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, environment and human health. Klocke and Eisenblätter [1] reported that 15% of the total cutting cost is due to the use of cutting fluids, while 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 efficiency and precision of metal cutting processes. However there are new alloys especially difficult for machining, for instance, 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 industry, where high speed cutting technologies are meeting serious difficulties to be introduced and which cannot be effectively cut without cooling even with latest coatings. One approach to enhance the machining performance in cutting of such materials is hot machining. Kitagawa and Meakawa [2] found that machining by softening the workpiece is 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 [3] and cryo-cooling [4] have also been introduced. Both techniques contribute to reduction of cooling lubricant consumption.

Machining with high-pressure cooling lubrication (HPCL) is also starting to be established as a method for substantial increase of removal rate and productivity in the metal cutting industry. Cooling lubrication 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. Cooling lubricants have a direct influence on the environment and manufacturing economics. By abandoning conventional cooling lubrication and using the technologies of dry machining or HPCL, the cost related to the usage of cooling lubricants can be reduced. Besides an improvement in the efficiency of the machining process, those principles can contribute to the environment concerns. The introduction of machining with reduced cooling lubricants requires suitable measures to compensate for the increase of friction and dissipation of the generated heat. Tools for dry machining have to incorporate special features relating to the low friction in the cutting zone and a high thermal resistance. Klocke et al. [5] have shown how turning of steel and cast iron materials can be performed completely under dry conditions with usage of currently available coated carbide tools that have high thermal resistance.

Cutting of such 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 HPCL 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 HPCL turning of hard-to-machine materials. All investigations are performed with conventional cutting speeds and using 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 lubrication efficiency, tool wear, and cutting forces.

2. HIGH PRESSURE COOLING LUBRICATION (HPCL)

In metal cutting, 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 material mechanical properties. The thermal impact mainly depends on the cooling lubrication capability as well as the maximum temperature reached in the cutting zone. Cutting performances can be improved with the control of tool-chip interface temperature and friction conditions in the cutting zone. HPCL is the method, which can be applied for higher cutting performance.

2.1 Working principle

Conventional cooling lubrication is not efficient enough to prevent extreme thermal conditions in the cutting zone especially when cutting advanced materials. Compared to the conventional cooling lubrication, the idea of HPCL is to inject a high pressure jet of emulsion in the cutting zone. The lathe should be fitted with high pressure equipment. This involves high pressure pump, high pressure tubing, and outlet nozzle fixed beside tool holder. A pump is supplied with filtered water or emulsion. A complete machine tool set is presented on Figure 1.

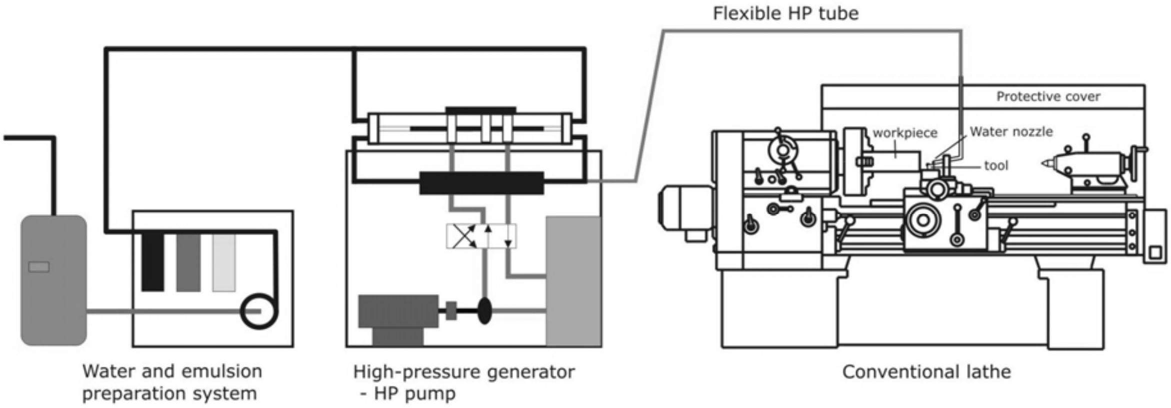

Figure 1: System configuration for turning with HPCL.

The jet can be applied in two ways (Figure 2):

With an external nozzle:

The jet is injected directly in between the rake face and the chip (Figure 2.a) or can be directed to the gap between the flank face and the workpiece (Figure 2.b).

Through internal channels:

The fluid is injected through the tool using small holes in the insert (Figure 2.c)

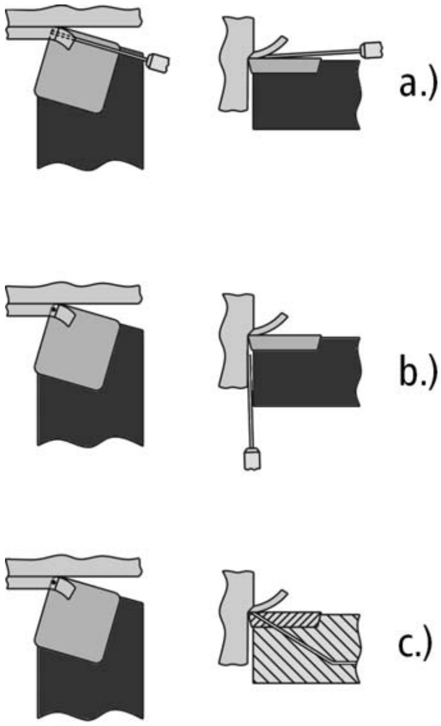

Figure 2: Different ways to apply high pressure cooling lubricant: a) between the rake face and the chip, b) into the clearance, c) towards the rake side through the tool.

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 to reduce the temperature in the cutting zone, but has no influence on chip breakability. In this investigation the realisation shown in Figure 1.a has been used. HPCL is applied on the rake face through an external nozzle that can provide higher machining performances and is easier to set on the conventional lathe.

2.2 Review of high pressure cooling lubrication

Pigott [6] was the first author to discuss the use of high pressure cooling lubricant in steel turning with high speed steel tools. He injected the cooling lubricant at a pressure of 2.76 MPa directly at the clearance of the tool (Figure 2.b) and he found that the temperature dropped by 24 °C and that tool life increased by 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 lubrication at low pressure and high flow rate. Moreover, the low speed of the cooling lubricant does not allow the lubricant to reach the cutting edge; a situation that favours the formation of built up edge and unfavourable heat dissipation due to which the chips are cooled to a higher extent than the tool and the workpiece.

In Yankoff [7] solution, the orifice is placed atop the exposed surface of the insert for ejecting high speed cooling lubricant at 20 MPa across the rake face of the insert and beneath the chips from the workpiece. Experiments reported in [6, 7] were conducted within a limited pressure range.

In extensive investigations by Ezugwu et al. [8, 9, 10], 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 difficult to machine nickel-based and titanium alloys. Ezugwu and Bonney [8] confirmed the feasibility of using HPCL in the rough turning of Inconel 718 with coated carbide tools. The investigation showed that the high pressure cooling lubricant increased lubrication. Another reported benefit was related to the decrease of tool-chip contact length, which could contribute to the decrease of temperature. In the next study Ezugwu et al. [9] assessed the whisker reinforced ceramic tool life during the machining of Inconel 718 at different cutting speeds and under different cooling lubricant pressures. It was proved that at all cutting speeds, tool life increases when the cooling lubricant pressure of up to 15 MPa was employed. However, when pressure is 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 high pressure cooling lubricant. Ezugwu et al. [10] also assessed the tool life of uncoated carbide and CBN tools when turning Ti-6Al-4V alloy using conventional and HPCL. When using CBN tools, tool life was increasing with cooling lubricant pressure throughout the pressure range tested. When uncoated carbide tool was used, tool life was increasing with the cooling lubricant pressure throughout the pressure range tested, from the conventional application to 15 MPa. When we further increased pressure to 20.3 MPa the opposite trend was observed. 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. They also stated that the optimum coolant pressure appears to be in relation to the total heat generated during machining.

Öjmertz and Oskarson [11] carried out machining experiments on Inconel with an injected high pressure coolant under pressure in the range of 80 to 380 MPa. The high pressure jet was applied directly into the tool-chip interface. It was found that cooling lubrication introduced by the high pressure jet 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 Chalmers University of Technology on jet assisted turning of steel [12, 13, 14, 15, 16]. In these investigations an extensive analysis of the possibilities for controlling the chip formation was reported. In [12, 13, 14] it is showed how to control the chip curl radius, chip-flow direction and chip breakage by setting the appropriate jet parameters. Significant reduction of temperature in the cutting zone and surface roughness due to the use of HPCL is reported in [15, 16]. The authors concluded that material properties determine whether high pressure or high flow have to be used to get the best cooling lubrication effect in the turning of soft stage steels with carbide tools.

External cooling lubrication is always applicable to external turning. However, it may be difficult in internal turning. Wertheim et al. [17] and Shoenig et al. [18] performed extensive research on high pressure lubricant supply through the tool rake face shown on Figure 2.c. Shoenig et al. [18] demonstrated jet assisted machining for the turning of titanium with uncoated carbide tools. The pressure applied was up to 345 MPa, and the cutting insert orifice was located near the cutting edge, where the compressive chip loads were about 276 MPa. The high pressure water jet application worked both as a source of coolant and as a hydraulic chip breaker. The tool life for titanium machining was improved by an average of 500%. It was reported that a coolant stream bends and floats the chip off the rake face and breaks it into small segments.

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 cooling lubricant at reduced flow rates and pressures larger than 50 MPa.

3. EXPERIMENTAL WORK

3.1 Experimental setup and equipment

In the experiments hard chromium platted and surface induction hardened steel Ck45 (AISI 1045) and nickel alloy - Inconel 718 were tested. Both materials are known to induce chip control problems. That makes them suitable for HPCL machining. The depth of the hardened surface layer for Ck45 was between 1.5 and 1.8 mm with a hardness of 58 HRc. The cutting tool inserts used in the experiments with Ck45 were coated carbide cutting tools – SANDVIK SNMA 120408 with Al_2O_3 coating, while Inconel with hardness 36 – 38 HRc was machined with coated carbide cutting tools – SANDVIK SNMG 12 04 08-23 with TiAlN coating. The inserts for Ck45 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 250 MPa pressure and 3 l/min flow capacity. Standard sapphire orifices of 0.25 mm, 0.3 mm and 0.4 mm diameter, commonly used in water jet cutting applications are mounted with a custom made tool clamping device that enables accurate cooling lubricant jet adjustments.

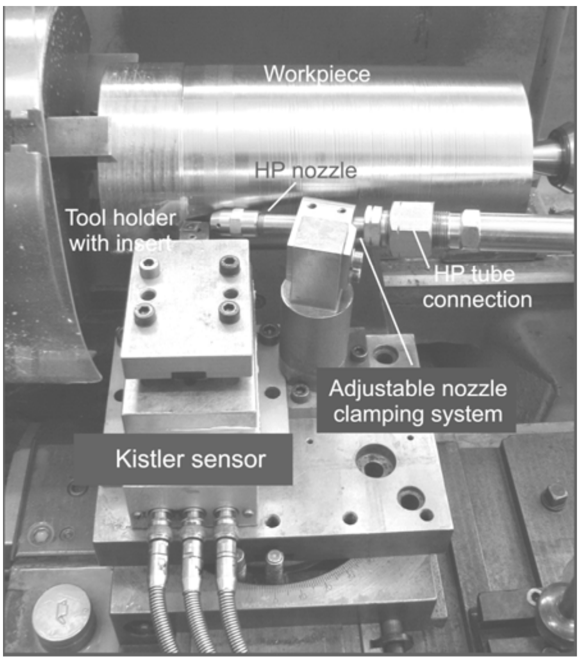

Figure 3: Machine tool setup used in experimental work.

A 0.3 mm diameter orifice was used for Ck45 cutting, while 0.25 mm and 0.4 mm were used for Inconel cutting. The cooling lubricant jet is directed to the cutting edge at a low angle of 5º with the rake face at the distance of 22 mm. The cooling lubricant 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. The experimental set up is shown in Figure 3.

3.2 Experimental sequence

Machining experiments were conducted in dry, conventional and HPLC conditions. The experimental sequence consists of two steps:

1. In the first step, screening experiments were conducted in order to determine cooling lubricant pressures that yield adequate chip breakability and cooling capability. Within this experimental step the influence of cooling lubricant pressure on the cutting forces was analysed.
2. In the second step, technological windows for all three cooling lubrication conditions were determined. The technological window sets the boundaries of the process cutting speed-feed rate operational area. The methodology involved measurements of the cutting forces and an analysis of the generated chips and was based on the French national standard NF E 66-520-6: Tool-Material Pair (TMP) [19]. 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 cooling lubricant condition were kept constant.

4. RESULTS AND EVALUATION

4.1. Screening experiments

Within the screening experiments on steel Ck45 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. 4. Insufficient cooling is related to a low coolant lubricant 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.

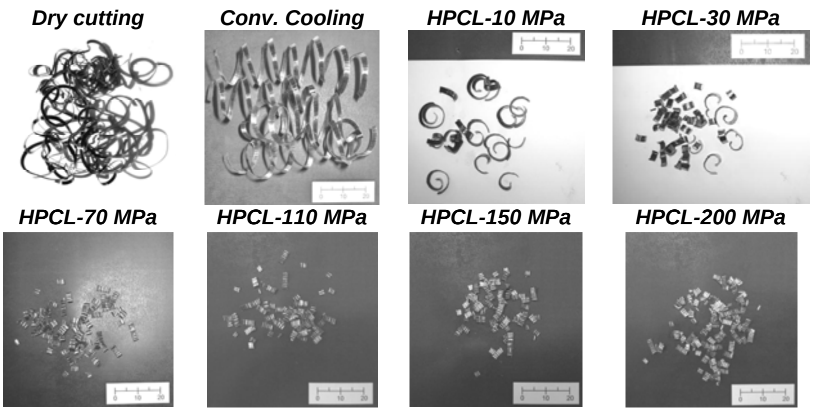

Figure 4: Chip forms regarding the cooling conditions and lubricant pressure for Ck45.

Within the screening experiments the influence of the cooling lubricant pressure on the cutting forces was analysed. The feed and penetration force decrease as soon as the HPCL was applied but no real trend can be noticed with the increase of the pressure. In the case of the main cutting force it is more difficult to verify a significant trend, whereas the small variations observed can be considered to be within the margin of measurement error.

For the subsequent experimental steps in HPCL machining of hardened steel Ck45, the pressure of 110 MPa was chosen. This pressure yields a flow of approximately 1.4 l/min.

The pressure for HPCL machining of Inconel was chosen regarding the pump capacity with aim to analyse the influence of cooling lubricant flow on cutting performance. Two different nozzles were used, namely 0.25 mm and 0.4 mm. The highest pressure achieved with large nozzle was 130 MPa. The cooling lubricant 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; this is 0.6 l/min. This flow rate could be achieved with smaller nozzle at pressure of 50 MPa. Within the screening experiments on Inconel 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 lubrication conditions. The colour of chips was brightly metal in all cases except in dry conditions as can be seen in Figure 5. This indicates that sufficient cooling was applied.

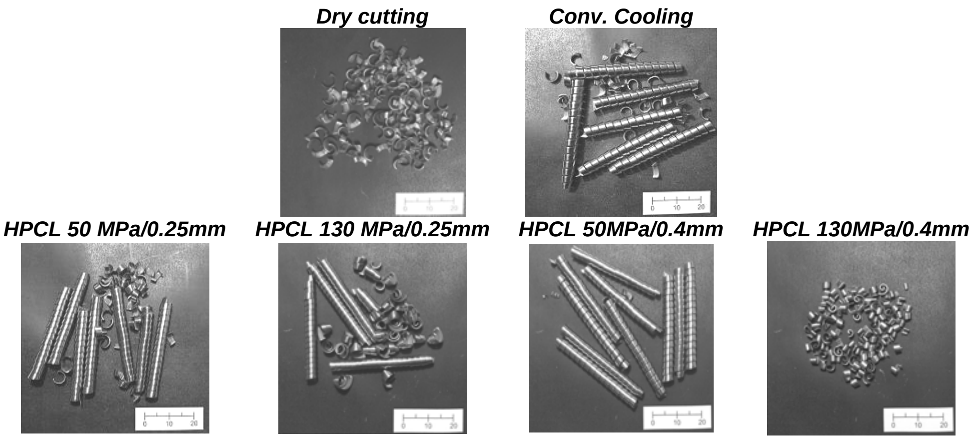

Figure 5: Chip forms regarding the cooling conditions in Inconel turning
(vc = 50 mm/min, f = 0.25 mm/rev, ap = 2mm).

4.2. Technological windows

Hard chromium platted and surface induction hardened steel Ck45.

Dry cutting:

In dry cutting, long, ductile chips that complicate the machining process were formed regardless of the cutting parameters. Figure 4 shows the undesired shapes of chips, which can jam around the tool and the workpiece.

Conventional cooling lubrication:

Cutting speed range: For these experiments the feed rate, f = 0.25 mm/rev, and the depth of cut, a_p = 2mm, were kept constant according to the TMP methodology. The minimum cutting speed is reached when significant changes in specific cutting forces and/or surface finish were observed. The maximum cutting speed was determined by monitoring the surface finish and the shape of the chips. At cutting speeds higher than v_c = 115 m/min the surface finish roughness began to increase and the chips were getting undesired shapes. Figure 5 shows that the operational range for cutting speed for this TMP is between v_c = 90 m/min and v_c = 115 m/min.

Feed rate range: For these experiments the cutting speed, v_c = 98.5 mm/min, and the depth of cut, a_p = 2 mm, were kept constant. No significant alterations in specific cutting force could be observed during experiments. Therefore, the shape of the chips was the operational range selection criterion. At feed rates higher than *f* = 0.27 mm/rev, the chips got undesired shapes. The operational range for feed rates for this TMP is between *f* = 0.224 mm/rev and *f* = 0.265 mm/rev. At conventional cooling the cutting fluid flow rate was approximately 6 l/min.

High pressure cooling lubrication (HPCL):

Cutting speed range: As in the case of conventional cooling lubrication, for all experiments the feed rate, *f* = 0.25 mm/rev, and the depth of cut, a_p = 2 mm, were kept constant. The pressure was set to 110 MPa. In HPCL the minimum cutting speed, v_c = 90 m/min, has been clearly determined by the evolution of a specific cutting force at a low cutting speed, which is the result of a built-up edge (BUE). The maximum cutting speed, v_c = 158 m/min, was chosen in a way that the experiments could run safely. The generated chips had a desired shape.

Feed rate range: As in the case of conventional cooling lubrication, for all experiments the cutting speed, v_c = 98.5 m/min, and depth of cut, a_p = 2 mm, were kept constant. The pressure was set to 110 MPa. The lower limit for feed rate is determined by the size of the chips. At low feed rates, *f* = 0.16 mm/rev, chips were too short and could damage the slides of the lathe during the operation. At feed rates higher than *f* = 0.36 mm/rev, vibrations and long chips were generated. During the experiments the specific cutting force was just slightly higher than its theoretical value.

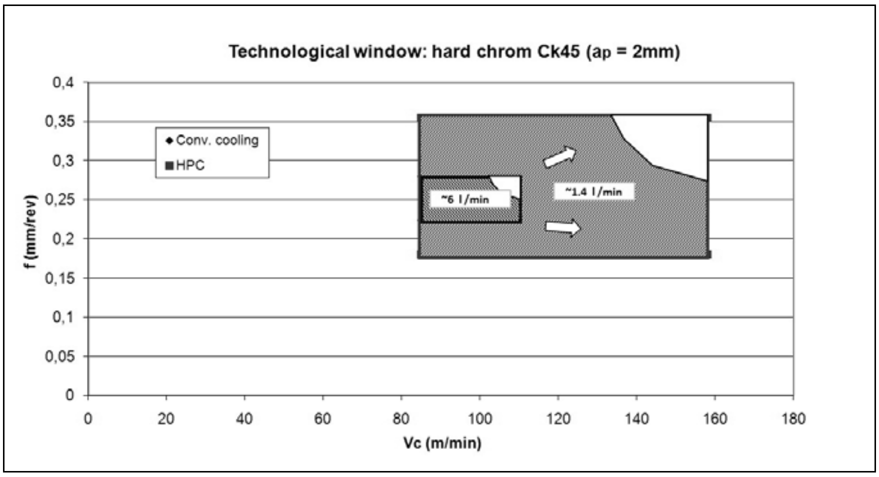

Figure 6: Technological window for TMP in HPCL and conventional cooling lubrication of hardened steel Ck45.

According to the maximum rotation speed limitation of the spindle, cutting speeds higher than 200 m/min have not been tested and the upper limit was fixed to 158 m/min for safety reasons. Fig. 5 shows operational areas for TMP for the case of conventional cooling and HPCL conditions.

Inconel 718

Dry cutting:

In dry cutting of Inconel, burned, golden colour chips were formed regardless of the cutting parameters. Beside really high temperature in cutting zone was observed. The chips got red colour while cutting and the insert was worn immediately. The results have shown that dry cutting condition is not appropriate for this material at such depth of cut.

Conventional cooling lubrication:

Cutting speed range: For these experiments on Inconel the feed rate, *f* = 0.25 mm/rev, and the depth of cut, a_p = 2mm, were kept constant according to the TMP methodology. The minimum cutting speed is reached when significant changes in specific cutting forces were observed. The maximum cutting speed was determined by monitoring the surface finish and the shape of the chips. At cutting speeds higher than v_c = 81 m/min the vibrations started. Figures 7 and 8 show that the operational range for cutting speed for this TMP is between v_c = 50 m/min and v_c = 81 m/min.

Feed rate range: For these experiments the cutting speed, v_c = 50 mm/min, and the depth of cut, a_p = 2 mm, were kept constant. No significant alterations in specific cutting force could be observed over whole range of feed rates. Therefore, the shape of the chips was the operational range selection criterion. At feed rates lower than *f* = 0.224 mm/rev, the chips got very long, undesired shapes, while at feed rates higher than *f* = 0.28 mm/rev the vibrations were generated. The operational range for feed rates for this TMP is between *f* = 0.224 mm/rev and f = 0.28 mm/rev. At conventional cooling the cutting fluid flow rate was approximately 6 l/min.

<u>High pressure cooling lubrication (HPCL)</u>:

In HPCL of Inconel two different orifice diameters were tested, namely 0.25 mm and 0.4 mm. The pressures were also set on two levels, 50 MPa and 130 MPa. These settings gave 4 different flows of cooling lubricant. TMP methodology was performed for all 4 conditions and influence of cooling lubricant on cutting capability were analysed.

At pressure 50 MPa no evident enlargement of technological window comparing to conventional flooding was achieved when smaller nozzle was applied (Figure 7). This is probably because of low contribution of HPCL in chips breakability and insufficient cooling lubrication with such low jet momentum. The flow rate of cooling lubricant in this pressure/nozzle (50 MPa/0.25 mm) combination was only 0.6 l/min. At pressure of 130 MPa with same nozzle, better results were achieved. The technological window was enlarged on the side of lower cutting speeds and lower feed rates. This can be seen on Figure 7, which shows operational areas for TMP for the case of conventional cooling and HPCL conditions for 0.25 mm nozzle.

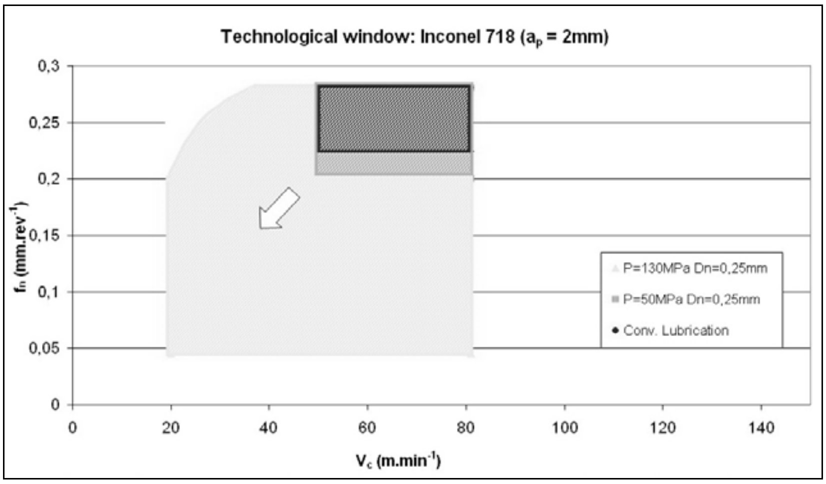

Figure 7: Technological window for TMP in HPCL and conventional cooling lubrication of Inconel 718 (nozzle diameter Dn = 0.25 mm).

Results with considerably better productivity and flexibility were achieved with larger nozzle (0.4 mm). Even with lower pressure level the cutting performance was increased, which represents technological window in Figure 8. Both higher and lower cutting speeds and feed rates compared to conventional cooling lubrication can be used with such nozzle for both high pressures applied.

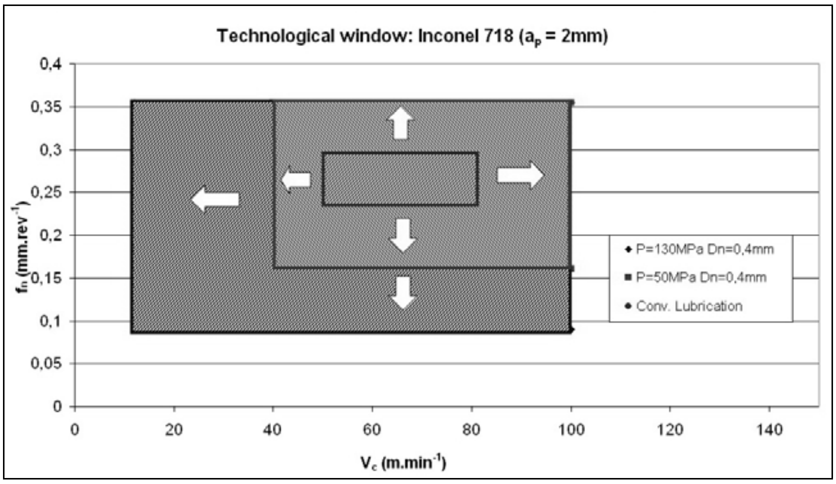

Figure 8: Technological window for TMP in HPCL and conventional cooling lubrication of Inconel 718 (nozzle diameter Dn = 0.4 mm).

Figure 9 shows a consumption of cooling lubricant at different cooling lubrication conditions. The highest improvement in cutting performance in connection with lowest cooling lubricant consumption is achieved with larger nozzle and lower pressure. In this case almost quarter of cutting fluid is used compared to conventional flooding.

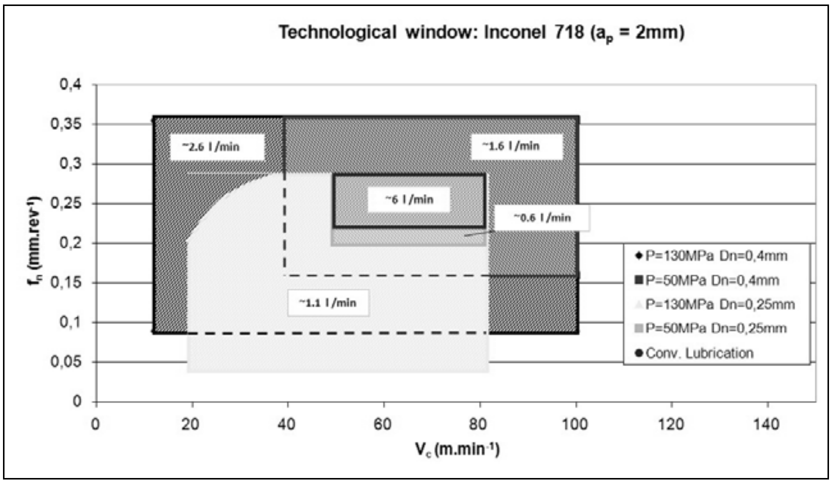

Figure 9: Consumption of cooling lubricant at different cooling lubrication conditions.

5. 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 lubrication. In the first case dry cutting is performed. In the second and the third case conventional and HPCL methods are employed. The experimental work has proved that the turning of both materials, namely chromium platted and surface induction hardened steel Ck45 and Inconel 718 with coated carbide tools at conventional cutting speeds is not possible in dry cutting conditions. The process capabilities of conventional and HPCL 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 HPCL precedence over conventional cooling lubrication in the turning of both hard-to-machine materials with coated carbide tools are:

For chromium platted and surface induction hardened steel Ck45,

- 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.
- Significant increase in chip breakability.
- All machining advantages mentioned above were achieved with a reduction of cooling lubricant consumption by four times.

For Inconel,

- Extension of the operational area for a given tool-material pair strongly depends on nozzle diameter and pressure applied. More specific, with smaller nozzle (*dn* = 0.25 mm) and lower pressure (*p* = 50 MPa) no significant improvement comparing to conventional cooling lubrication 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 is 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.
- Significant increase in chip breakability.
- All machining advantages mentioned above were achieved with a reduction of cooling lubricant consumption. The best results considering higher productivity and lower cooling lubrication consumption were attained with combination of larger nozzle (*dn* = 0.4 mm) and lower pressure (*p* = 50 MPa).

The researches on HPCL technology will continue their activities based on knowledge gained in this investigation on hard to machine materials like Inconel 718, S290 (Boehler TM steel) and other. A more detailed analysis is planned, including online cutting zone temperature measurement, surface finish integrity analysis etc.

6. ACKNOWLEDGMENT

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