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RESEARCH

Possibilities of Application of High Pressure Jet Assisted Machining in Hard Turning with Carbide Tools

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A B S T R A C T

High Pressure Jet Assisted Machining (HPJAM) in turning is a hybrid machining method in which a high pressure jet of cooling and lubrication fluid, under high pressure (50 MPa), leads to the zone between the cutting tool edge and workpiece. An experimental study was performed to investigate the capabilities of conventional and high pressure cooling (HPC) in the turning of hard-to-machine materials: hard-chromed and surface hardened steel Ck45 (58 HRc) and hardened bearing steel 100Cr6 (62 HRc). Machining experiments were performed using coated carbide tools and highly cutting speed. Experimental measurements were performed for different input process parameters. The cooling capabilities are compared by monitoring of tool wear, tool life, cooling efficiency, and surface roughness. Connection between the tool wear and surface roughness is established. Experimental research show that the hard turning with carbide cutting tools and HP supply CLF provides numerous advantages from the techno-economic aspect: greater productivity, reduce of temperature in the cutting zone, improved control chip formation, extended tool life, low intensity of tool wear, surface roughness in acceptable limits, significant reduce of production costs related to the CLF.

1. INTRODUCTION

In modern cutting processes, the general trend is dry machining. However, there are materials, which due to the high temperature that develops in the cutting zone, cannot be dry machined, even with the most modern tools with coatings. These are called hard - to -cut materials such as: austenitic stainless steels, high-temperature resistant nickel and cobalt alloys, titanium alloys, and hardened steels. Machining of these materials requires the use of a cooling and lubrication fluid (CLF).

It is well known that cutting fluids are influencing the complete cutting process. This influence is mostly visible through change of cutting tool life, where using of cutting fluids lids to an increase of tool life and decrease of total cutting costs. It is also common knowledge that cutting forces are decreasing which also mean that power consumption of machine will be lower [1]. Economical production requires reducing of tool wear to minimize interruption in the manufacturing process and tool cost. From the structure of the cost of machined part, it can be concluded that the cost of CLF participate 15%, costs of tools 10% and costs of energy consumption 4% of total costs.

Machining process for workpiece materials that are hardened above 45 HRc and up to 65 HRc is a hard turning. In the manufacturing chain, the inductive hardening process is followed by finishing operation that generates the component's final geometry. Traditionally, the finishing operations are grinding processes, but within the last years the performances of hard cutting operations have been drastically improved. The study of Klocke et al. (2005) has shown that hard cutting offer a higher flexibility, increased material removal rates, increased tool life, reduction of cutting temperature and tool wear, improvement of chip breakability, reduced power consumption and the possibility of machining with reduced coolant consumption [2].

In the literature, as well as in practices it can be traced to a variety of approach to the solution of this the problem and improve the machinability completely [3]. In order to increase productivity, quality of machining and machinability hard-to-cut materials, a variety of methods and techniques of cutting have been developed. One solution is a self-driven rotating turning tool. This mechanism bring some advantages such as significantly extended tool life, lower cutting temperatures, higher material removal rates, a very fine-treated surface, and very little change in the structure of the treated surface, in short, an improved machinability. Precision rotating tool shows some weakness in manipulating with them, especially with tools larger diameter, as well as that stepwise workpieces cannot be machined. In order to improve the machinability of complex materials many hybrid procedures with mechanical or thermal support for the cutting process, such as ultrasonic assisted turning, laser-assisted turning and cryogenic cutting, are developed. Most implementations of hybrid technologies include turning, it is estimated that turning occupies 40 % all treatments with the cutting, as well as its kinematics provides access support process. The previously described technology and required additional equipment have an additional technical limitations and sometimes even higher processing costs.

Development of materials (super alloy) for specific applications such as components for aircraft jet engines, gas turbines and biocompatible materials in medicine, require materials of high hardness, strength and toughness, resistance of corrosion and high temperature. In addition, the above-mentioned hybrid processes combined with use of cutting with high pressure, the degree of material removal and machining productivity is significantly increased. The turning of the cooling and lubrication at high pressures is a very effective method that enables higher productivity, reduces temperature in the cutting zone and improved control chip formation, depending on the pressure and flow of CLF [4]. In addition, CLF have a direct impact on the environment and economy of production. By replacing the conventional type of cooling application with HP supply CLF significant reduce production costs related to the CLF is achieved [5-7].

Hard turning usually requires high cutting speeds and advanced cutting tool materials such as CBN, PCD and ceramics. Hard cutting with coated carbide tools, low cutting speed and conventional cooling, usually results in significant problems concerning extremely long chips and severe adhesion wear mechanisms. By applying HPC at flow rate 1.4 l/min, the friction and the heat induced in the tool–chip interface can be reduced.

1.1 A short literature review

Previous studies in the field of hard machining have been focused on exploring possibilities to improve cutting conditions, through the introduction of special cutting tool materials and geometry, cooling techniques, or through the use of controlled cutting conditions as a result of modeling and optimization. In the paper [8], authors analyzed application of high pressure coolant supply in machining of aerospace alloys with carbide tools. The result of this study was extended tool life and lower thermal loads. CBN cutting tool is very sensitive to temperature load and some authors [9] were analyzed thermal load of these tool materials. In the paper [10], authors used a high pressure coolant technique on different pressures and discovered the reduction of tool wear, and reduced tool-chip contact length. Kramar et al. [11] investigated different conditions of cooling, and result of this study was that pressures above 40 MPa lead to increased tool life, and chip breakability. Researchers in papers [12] and [13] were concluded that CBN tool offered good wear resistances in the machining of 100Cr6, hardened to 60 HRc. Results of investigations in papers [14] and [15] give recommendations for the favorable range of the machining parameter values that enable the energy efficient machining of bearing steel hardened to 60 HRc, based on modeling. The influence of cutting parameters on hard turning with CBN tools was investigated in paper [16]. The influence of CBN cutting tool geometry on surface roughness and chip morphology was studied in [17] and [18]. Aneiro et al. successfully processed the AISI 4340 steel hardened to 50 HRc with coated carbide tool at higher speeds [19]. Also, in some papers, authors analyzed the output process parameters on hard turning with CBN tools, [20] and [21].

The possibility of application of carbide tools in hard turning, by using a special cooling and lubrication technique were the focus of research in this paper.

This paper presents the results of investigation of the author's team in area of hard turning [22-25]. In this investigation the capabilities of conventional and HPC in hard turning on two hard-to-machine materials (hard-chromed and surface hardened steel Ck45 (58 HRc) and hardened bearing steel 100Cr6 (62 HRc)) are compared. All machining experiments are performed with coated carbide tools and cutting speeds up to 160 m/min (expect for steel Ck45 (58HRc) where the speed was up to 250 m/min. The performances of different cooling conditions are evaluated on the basis of tool wear, tool life, cooling efficiency and surface roughness.

2. EXPERIMENTAL DETAILS

The experimental investigation was performed on a conventional lathe (Fig. 1). In the flooding technique, CLF was delivered at the top of the machining zone, from a distance of approximately 150 mm at 6 l/min. CLF was directed to the non-machined workpiece surface and the rake surface of the cutting tool insert, Fig. 2.

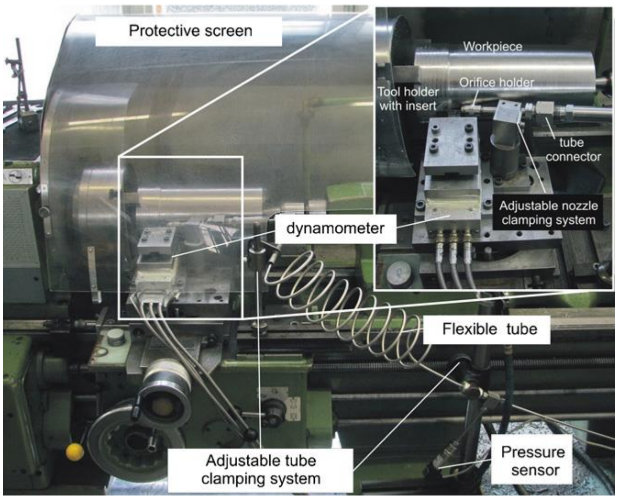


Fig. 1. Machine in experimental work with HPJAM.

Fig. 2. Position of conventional flooding

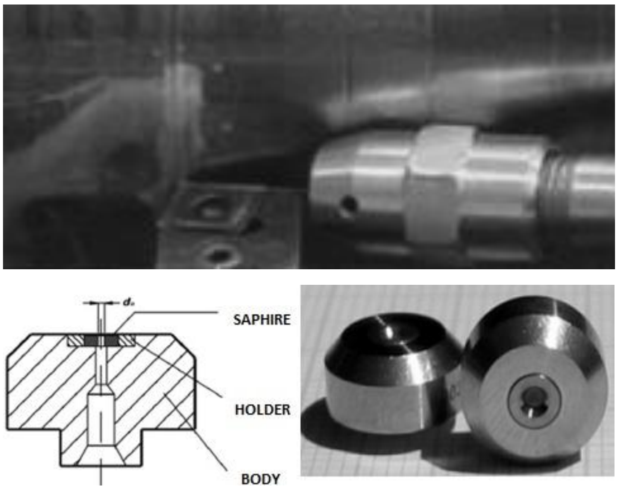


Fig. 3. The jet injected directly between the rake face and the chip (above), sapphire nozzle (below).

In HPJAM, the jet was directed toward the cutting edge at a low angle directly between the rake face and the chip (Fig. 3). For this application, a conventional universal lathe was fitted with a high pressure plunger pump with a flow rate capacity of 10 l/min and pressure of 150 MPa. The jet was directed normal to the cutting edge and under angle of 30° from clearance face at a low angle 5° with the tool rake face.

Monitoring and measurement of tool wear was performed using a tool microscope TM-MITOTOYO 510 equipped with high-resolution camera. Surface roughness was measured using a mobile measuring device MITOTOYO SURFTEST SJ-301, Fig. 4.

Fig. 4. Surftest SJ-301 and tool microscope.

During the experimental investigation, following parameters were measured and analyzed: flank tool wear (*VB*), wear on minor flank face (*VB'*) and the size of the crater on the rake face (b_w). The measurement of the selected parameter of tool wear during cutting enables the creation of the experimental curves of wear [25]. By defining the wear resistance of tools for a given criterion VB_k, the tool life *T* can be determined. Due to wear of tools, values of surface roughness were measured, as follows: mean values of roughness (R_a) and maximum height of roughness (R_y).

2.1 Experimental work with Ck45 (58 HRc)

One of workpieces materials used in the experimental investigation is construction steel used for highly loaded parts in mechanical engineering (untreated carbon steel Ck45 - surface induction hardened on 58 HRc). Experimental conditions are: tool - Al_2O_3 coated carbide cutting tools SNMA 120408 KR 432 without chip breaking geometry on the rake face (Fig. 5), tool holder PSBNR 2020K 12 (producer Sandvik), CLF -5,5% emulsion of vegetable oil.

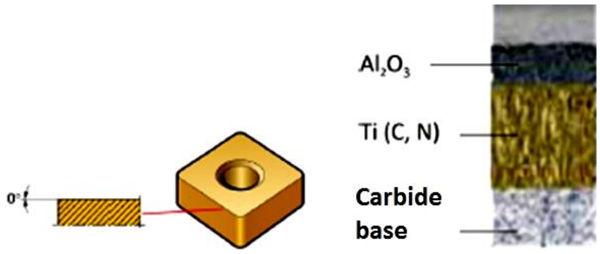


Fig. 5. Coated carbide tool SNMA 120408 KR 432.

For the analysis of the jet pressure influence on the cutting process, different CLF pressures were applied (10 - 200 MPa), while the cutting speed, v_c = 98.5 mm/min, feed rate f = 0.25 mm/rev and depth of cut a_p = 2 mm, were kept constant. Chip breakability is excellent in every case of HPJAM. During the experimental investigation, it was noticed that the pressure higher than 110 MPa is not achieved by further improving chip breaking, so that the test tool wear and surface roughness done in these conditions. Efficiency CLF techniques is analysed by means of tool wear and surface roughness in following conditions: cutting speed, v_c = 98.5 mm/min, feed rate f = 0.25 mm/rev and depth of cut, a_p = 2 mm, pressure 110 MPa, diameter nozzle 0,3 mm.

Table 1. Tool wear in conventional cooling in turning of Ck45 (58 HRc) [24].

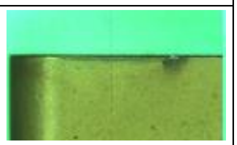
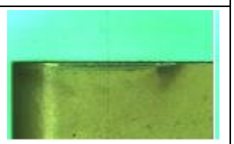
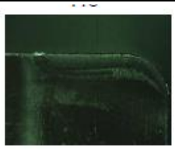
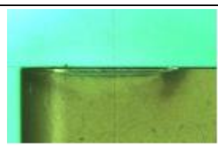
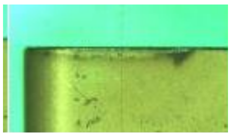
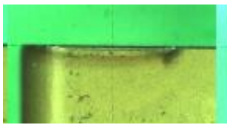
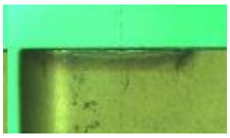
Time T [min]	Wear on rake face	Wear on flank face
0.5		
1.2		
1.9		

Table 2. Tool wear in HPJAM of Ck45 (58 HRc) [24].

Time T [min]	Wear on rake face	Wear on flank face
1.4		
3.9		
10.0		

As a criterion of wear, the value VB_k = 0.1 mm was adopted, at which the tool life should be evaluated. Images in Table 1 and Table 2 show that wear on flank face is uniformly for both CLF techniques. It can be seen a small notch at the place where the cutting blade cuts workpiece surface. This is probably due to the hard surfaces of the workpiece coated with chromium and friction with chip sharp edges.

Results on Fig. 6 shows that tool is worn for less than 2 minutes using conventional flooding for the selected criteria VB_k=0,1 mm, but for HPJAM tool is worn for about 10 minutes. The consumption of coolant in the case of HPC is more than four times lower than in the case of conventional cooling.

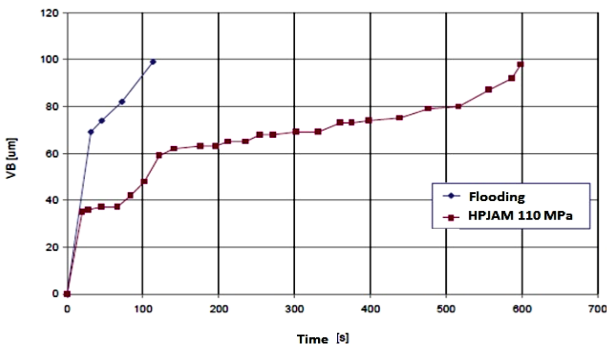


Fig. 6. Wear of tool SNMA 1204 08 KR in turning Ck45 (58HRc), a_p=2mm, v_c=98,5m/min, f=0.25mm/rev [22].

The Fig. 7 shows types of tool wear SNMA 1204 08 KR in turning Ck45 (58HRc) using HPJAM: zone A – notch wear, zone B - crater wear on the rake face dimensions of about 0.45 x 0.08 mm, C - erosion wear in the area where the jet strikes the surface of the tool.

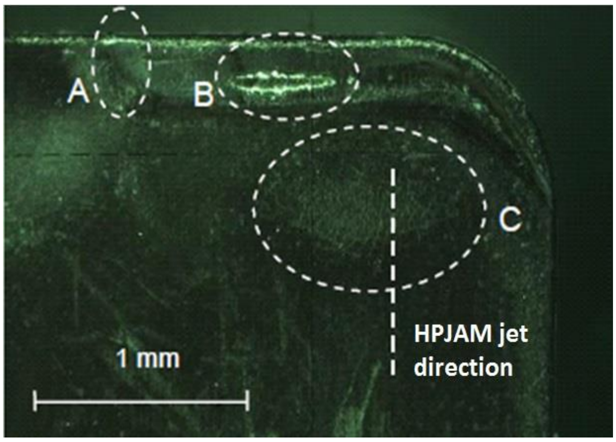


Fig. 7. Types of tool wear in turning Ck45 (58HRc) with HPJAM, p = 110 MPa.

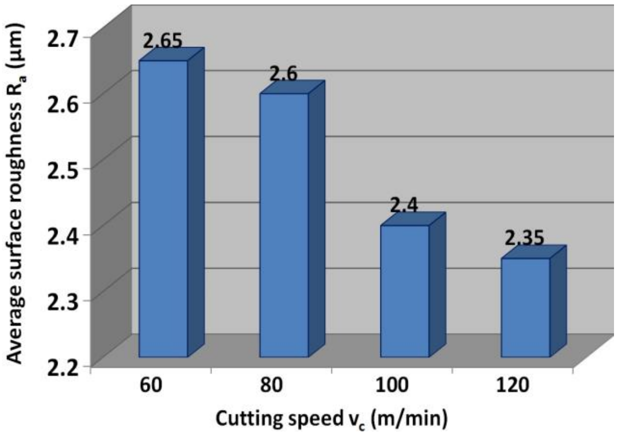


Fig. 8. Surface roughness Ra in turning of Ck45 (58 HRc, SNMA 120408 KR 432, f = 0.25mm/rev, a_p = 2mm; flooding).

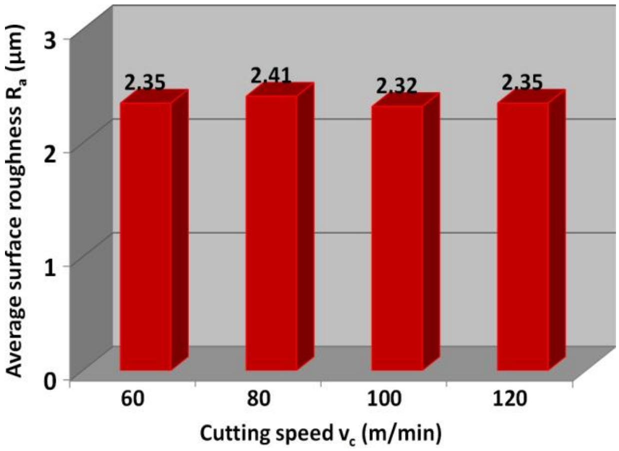


Fig. 9. Surface roughness Ra in turning of Ck45 (58 HRc, SNMA 120408 KR 432, f = 0.25mm/rev, a_p = 2 mm; p = 110 MPa, D_n = 0.3 mm, HPJAM).

Fig. 8 and 9 show the influence of the cutting speed and Figure 10 show influence of feed rate on surface roughness R_a.

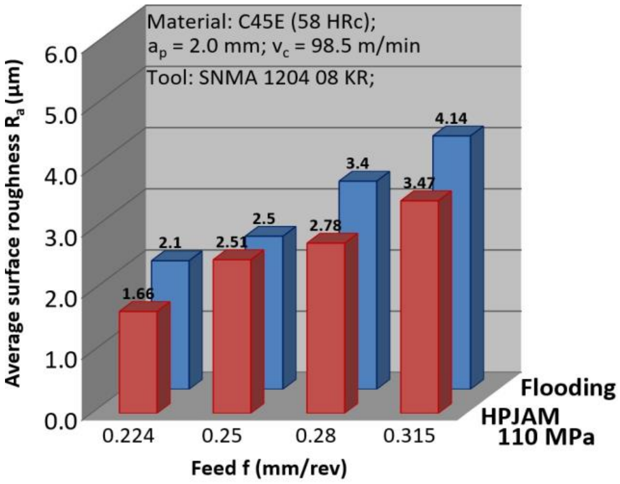


Fig. 10. Surface roughness Ra in turning of Ck45 (58 HRc) for different CLF techniques

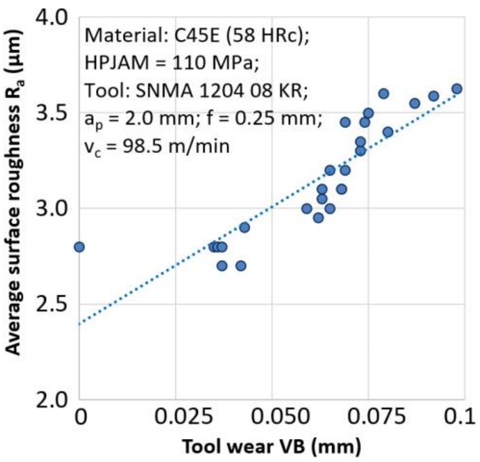


Fig. 11. Surface roughness Ra in turning of Ck45 (58 HRc) for different CLF techniques.

In Fig. 10 it can be seen that the surface quality is slightly improved when HPJAM was used, compared to conventional flooding. Since the application of HPJAM was in the semi-finishing and roughing operations the effect is not so important. Influence of tool wear on surface roughness R_a in turning of Ck45 (58 HRc) are presented on Fig. 11. With increase of tool wear, the surface roughness is increasing, as expected. Basic conclusions in turning of steel Ck45 with hardness 58 HRc regarding of tool life and surface roughness and the application of various CLF technique are as follows:

- the heat-treated steel can be adequately treated with the cutting insert, which is not suitable for this material (carbide tool without chip breaker),
- HPJAM is very important and allows the processing of hard materials without chip breaker,
- Excellent brittleness chips with HPJAM,
- using HPJAM can significantly increase the area of operability - technological window (for ~ 45 % of the maximum cutting speed and ~ 25 % of the maximum feed),
- For the selected criteria, in the case of HPJAM tool life was approximately five times longer than in the case of conventional cooling,
- The consumption of coolant in the case of HPC is more than four times lower than in the case of conventional cooling,
- For both CLF delivery techniques (conventional flooding and HPJAM) similar surface roughness was obtained.

2.2 Experimental work with 100Cr6 (62 HRc)

Second workpiece materials used in experimental investigation was alloy bearing steel 100Cr6, hardened to 62 HRC. This steel is very difficult to machining and dominantly is processed with CBN tool inserts. Main target was to investigate the capability of hardened steel processing using carbide tool insert and HPJAM, which is much cheaper than CBN tool insert.

Cutting tool used in experiments was carbide insert with nano-coating CNMG 1204 08 MF5, SECO producer, tool holder: PCBNR 2525 M12 (Fig. 12). Cutting fluid was 3% emulsion of vegetable oil. CLF technique was HPJAM, pressure was set to 50 MPa and flow rate to 2.0 $l\cdot min^{-1}$, diameter of nozzle was 0,5 mm. Input parameter: cutting speed v_c (65, 85, 100, 120 m/min), feed f (0,08; 0,125; 0,16; 0,2 mm/rev) and constant cutting depth, a_p =0,5 mm.

Fig. 12. Carbide insert CNMG 1204 08 MF5, internal designation TH1000 (SECO producer)

Experimental testing of tool wear was conducted in specific cutting conditions: the flank wear reaches approximately 0.25 mm or an interval of time of cutting reaches value of 20 min (see Fig. 13 and Table 3).

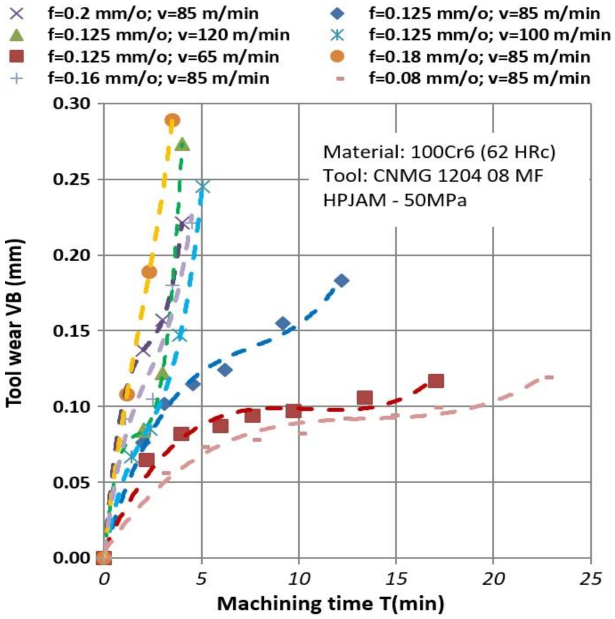
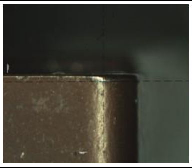
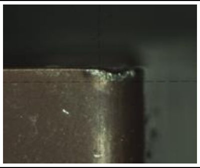


Fig. 13. Tool wear in turning of steel 100Cr6 with HPJAM for different cutting conditions, a_p=0,5 mm.

In Table 4, results of tool life and parameters surface roughness (R_a, R_y) for different cutting conditions are presented. Parameters Ra and Ry are presented for the first and last measured value of tool wear (at the moment immediately before the dismissal of tool). Analysis of results shows when feed and cutting speed increase, tool life decrease (see Table 3 and Table 4), but significantly increase productivity, i.e. material removal rates (*MRR*).

Table 3. Tool wear in turning steel 100Cr6 (HPJAM) ap =0,5mm, f=0,125 mm/rev vc=85 m/min.

Time T [min]	Wear on rake face	Wear on flank face
2.6		
13.2		

Experimental studies have shown that, in terms of tool wear and productivity of processing, optimal results achieved with lower values of feed and cutting speed, i.e. cutting speed 85 m/min and feed 0.08 mm/rev (see Fig. 13).

Results in Table 4 show that the influence of cutting speed on tool wear is the higher, expressed in percentages, than feed. Intensive tool wear is a result of high contact pressure on the cutting tool edge and intense heat generation during machining of hard-to-machining steels such as 100Cr6.

Table 4. Tool wear in turning steel 100Cr6 (HPJAM) ap =0,5mm, f=0,125 mm/rev vc=85 m/min.

Feed f [mm/o]	Cutting seed v [m/min]	Tool life T [min]	Ra [μm] on start	Ra [μm] on end	Ry [μm] on start	Ry [μm] on end
0.200	85	4.0	0.91	0.96	3.98	4.51
0.125	85	13.2	0.48	0.50	2.51	2.88
0.125	120	4.0	0.52	0.57	2.61	2.93
0.125	100	5.1	0.53	0.58	2.86	3.62
0.125	65	17.1	0.58	0.63	3.18	3.28
0.180	85	3.5	0.86	0.99	3.93	4.67
0.160	85	4.5	0.85	0.97	3.90	4.22
0.080	85	22.7	0.36	0.62	2.12	3.35

In cutting conditions when feed increases, at the same values of cutting speed, the surface roughness significantly increases, but when the cutting speed increases, with the same values of feed, better quality of processing is achieved, see Fig. 14.

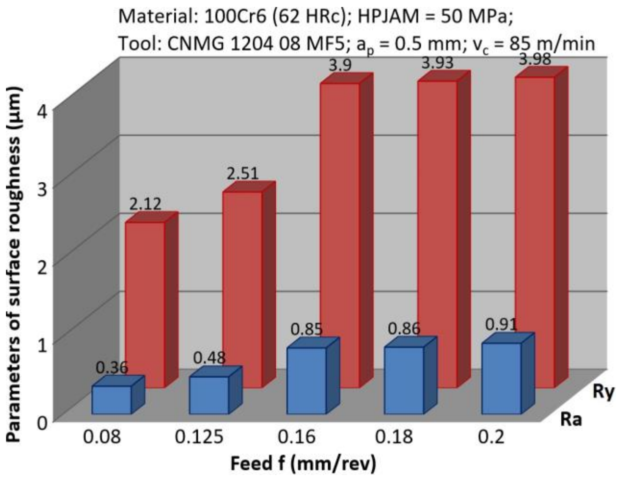


Fig. 14. Surface roughness for different feed during machining of 100Cr6 [26]

Based on the presented results in processing hard-to-machine steel, it can be concluded that the processing of these materials can be achieved with carbide tools by applying HPJAM in conditions semi rough and rough machining.

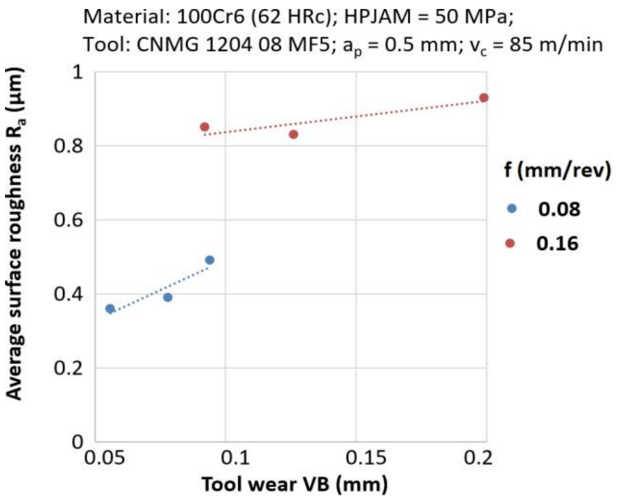


Fig. 15. Dependence of surface roughness on tool wear during turning 100Cr6.

The results in Fig. 15 show that with increased tool wear, there is also an increase in the parameters of surface roughness, when applying HPJAM. The increase in parameters of surface roughness is more pronounced for higher values of feed.

3. CONCLUSION

Main target was to investigate the capability of hardened steel processing using carbide tool insert, because mentioned material are processed dominantly with CBN tool inserts, which are much more expensive than the carbide tool inserts. Experimental study on capabilities of two techniques of cooling and lubrication (conventional flooding and high pressure jet assisted machining in the turning) was evaluated in this paper.

Experimental research was conducted on two hard-to-machine materials: Ck45 (58 HRc), and 100Cr6 (62 HRc). There were used coated carbide tools and highly cutting speed (up to 160 m/min). The capability of cooling is characterized by tool wear and surface roughness parameters. During tool wear, surface roughness parameters (R_a and R_y), were evaluated, and relation between the tool wear and surface roughness is established.

Basic conclusions in turning of steel Ck45 (58HRc) regarding of tool life and surface roughness and the application of various CLF techniques are:

- For the selected criteria (VB = 0.1 mm), in the case of HPJAM tool life was approximately five times longer than in the case of conventional cooling.
- Tool wear in HPJAM is uniform and less notch wear is recognized compared to conventional CLF technique.
- The consumption of coolant in the case of HPC is more than four times lower than in the case of conventional cooling.
- The changes in roughness were noticed as a consequence of the increasing tool wear. Compared to conventional cooling can be noticed that the surface roughness the slightly higher in HPJAM techniques due to action of high pressure jet to the surface.
- For both CLF delivery techniques (conventional flooding and HPJAM) similar surface roughness was obtained.

Results of experimental investigations indicate that HPJAM techniques can be successfully used for hard turning of steel 100Cr6 (62 HRc):

- The significant increase in chip breakability was achieved by use of HPJAM.
- Significantly reduction of the consumption of cutting fluid in comparison to conventional machining.
- The influence of cutting speed on tool wear is higher expressed in percentages than influence of feed. Intensive tool wear is a result of high contact pressure on the cutting tool edge and intense heat generation during machining.
- Experimental studies have shown that, in terms of tool wear and productivity of processing, optimal results were achieved with lower values of feed and cutting speed.

Results of presented experimental investigation show that the hard turning with carbide cutting tools and HP supply CLF provides numerous advantages from the techno-economic aspect: greater productivity, reduce of temperature in the cutting zone, improved control chip formation, longer tool life, significant reduce of production costs related to the CLF, similar surface roughness compared to conventional CLF technique.

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