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High-Pressure Cooling in Turning of Inconel 625 with Ceramic Cutting Tools

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Abstract

Machining of heat resistant aerospace materials such as Inconel 625 or Inconel 718 is characterized by low cutting speeds, high tool wear rate, and high production costs. The machinability of heat resistant super alloys is low due to high hardness and low thermal conductivity of the nickel-based alloys. The paper presents a study on turning of Inconel 625 with ceramic cutting tools with different methods for application of cutting fluid. It is shown that high-pressure cooling gives excellent chip breaking. The tool life of ceramic cutting tools is not improved by increased coolant pressure.

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Keywords: High-pressure cooling; Turning, Inconel 625

1. Introduction

Machining of nickel-based super alloys, such as Inconel alloys, is difficult due to the high strength and the abrasive particles in the alloys. The low thermal conductivity of the alloys contributes to a very high temperature in the cutting zone. Narutaki et al. [1] and Kitagawa et al. [2] have experimentally shown that in turning of Inconel 718 under conventional cooling, temperature on the rake face of ceramic tools reaches 900°C at the cutting speed of just 30 m/min and climbs to 1300°C at 300 m/min.

At high temperature the tool materials soften, thus they can be easier eroded by abrasion. In addition, high temperature promotes diffusion wear and can cause thermal shocks and fatigue. To achieve a reasonable tool life and to avoid other problems caused by high temperature, heat resistant alloys are often machined at cutting speeds as low as 30-100 m/min when using carbide tools [2].

One way to raise the efficiency in machining of these materials is to use more advanced tool materials. In machining of nickel-based alloys, ceramics cutting tools have become popular, and are often a more economical choice. Ceramics are very hard and have good abrasion resistance. Their melting point is very high, thus hardness is retained at elevated temperatures. Consequently, higher cutting speeds can be used, typically 200-300 m/min in turning of Inconel 718.

Despite the improvements achieved with ceramic tools, productivity in machining of aerospace materials is still relatively low. Therefore, additional measures need to be taken to deal with high temperatures. Traditionally, copious quantities of fluids have been poured onto the tool to extract the heat. This technique has proven to be effective in machining of steels and other materials, but, as shown by Kitagawa et al. [2], provides insufficient cooling in machining of heat resistant super alloys. Because of the high temperature, coolants are rapidly evaporated. As a result a layer of steam is created, which stops the fresh coolant from reaching the tool-chip interface thus rendering conventional flushing ineffective. The effect is sometimes referred to as the Leidenfrost effect. A few alternative techniques, including internal chilling of the insert, cryogenic-, CO_2- and high-pressure cooling, have been

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demonstrated [3]. The latter method seems to be particularly promising.

The principle behind the high-pressure cooling is to supply the cutting fluid in the form of a small jet. Already the early experiments [4] showed that, in rough turning of aircraft exhaust valves made in a nickel alloy, this method could increase the output per tool by over 18 times. Similar enhancement in the life of carbide inserts were obtained in turning of Inconel 718 [5, 6, 7] and Ti-6A1-4V [8] and grooving of Inconel 718 [9] and Ti-6A1-4V [10].

The high-pressure jet is directed between the rake face of the tool and the chip, or between the clearance face of the tool and the workpiece. In this way, cooling takes place closer to the highest temperature zone and is therefore more efficient [4, 11]. In addition, when the pressurized coolant penetrates under the chip, a hydro wedge [12] is created. It lifts the chip up, thus reducing its curl radius and the length of its contact with the tool. Such chips can be easier broken and flushed away by the jet. The latter advantage is mentioned in nearly every study on high-pressure cooling. Moreover, this technique has been reported to reduce friction [12, 13]. Therefore, cutting forces [12] and the tendency to form built-up edge [4] are reduced.

The good results achieved with high-pressure cooling in various applications indicates that the method could be used when machining aerospace materials with ceramic inserts. A concern, though, is the sensitivity of these tools to thermal stresses. Due to this weakness it is sometimes recommended to use no or very small quantities of coolant when machining with ceramics. However, due to the extreme temperatures generated in cutting of aerospace alloys, one or another way to dissipate heat has to be employed. Moreover, some ceramics, such as alumina reinforced with SiC-whiskers or SiAlON have improved resistance to thermal shocks [14]. It is therefore interesting to investigate whether the performance of ceramic tools, hence the productivity in machining of heat resistant materials, could be further improved by using high-pressure cooling.

1.1. High-pressure cooling with ceramic tools

Despite the impressive results achieved with high-pressure cooling when machining with carbides, there are only a few reported studies on the application of this technique when machining with ceramics. Ezugwu et al. [14] have experimented with turning of Inconel 901 with SiC-whiskers reinforced ceramic tools. They observed that cooling at a pressure of 14 MPa improved chip breaking. However, it generally led to shorter tool lives as compared to conventional flushing. The reason for this was mainly the accelerated notch wear. Analogous results were achieved by Ojmertz and Oskarson [15], who have tested rough turning of Inconel 718 with SiC-whiskers reinforced ceramic tools. They observed that high-pressure cooling led to better chip control, reduced tendency to built-up edge formation and therefore better surface quality as compared to dry machining. However, a clear tendency towards increasing depth-of-cut notch wear, which is said to be the main mechanism determining the life of SiC-whiskers reinforced ceramics, was observed as coolant pressure was increased from 80 to 360 MPa. The scatter of the data points was also bigger at higher coolant pressures. In addition to that, cutting force was increased. A similar work was performed by Ezugwu and Bonney [16], who have applied coolant at a pressure of 11-20 MPa in rough turning of Inconel 718 with SiC-whiskers reinforced ceramic tools. Despite the lower pressure they have also observed that jet cooling caused severe notching and therefore shorter tool life as compared to conventional flushing. Cutting force was also marginally increased, while chip breaking was improved. Promising results were achieved when Ezugwu et al. [17] repeated the experiments under finishing conditions. Besides the improved chip breaking, reduction in cutting force and generally increased tool life were observed at coolant pressures of 11 and 15 MPa. At 20 MPa, thought, tool life dropped significantly due to accelerated notch wear. Tool life was also shorter at 11 MPa when cutting speed was increased to 300 m/min. The above examples show that in general high-pressure cooling increases notch wear and therefore leads to shorter lifetime of SiC-whiskers reinforced ceramic tools. On the other hand, Ezugwu et al. [17] have demonstrated that correct selection of process parameters and coolant pressure can have an opposite effect. Vagnorius and Sørby [18] showed that high-pressure cooling could increase tool life by approximately 20% when machining Inconel 718 with SiAlON tools. When high-pressure cooling was used the notch wear was relatively high, but the general flank wear was lower. In addition, the variability of the tool wear was lower. Moreover, all studies on high-pressure cooling with ceramic tools report improved chip breaking, which is a considerable advantage, especially in automated manufacturing.

2. Experiments

2.1. Experimental set-up

Experiments were performed with a Hessapp DV80 lathe with an auxiliary pump, which delivers high-pressure coolant to the outlet on the tool turret. From this point, coolant is transported via a copper tube to specially designed insert clamp with internal coolant channels (∅2.0 mm). The angle between the rake face and the jet was close to 0° and the distance from the nozzle to the target point was 5 mm. The test piece was a cylinder with a diameter of 400 mm. The setup is shown in Figure 1.

The ceramic inserts used in the tests were round SiAlON inserts, Sandvik Coromant RCGX 12 07 00 E CC6060, with edge rounding radius of 0.04 mm. According to manufacturer's specification, the grade used in our experiments was developed specially for machining of heat resistant super alloys.

2.2. Experimental procedure

The cutting data used in the tests are shown in Table 1. The tests were carried out as face turning of the top surface of the test piece. The tool paths for the tests were programmed in such a way that the cutting tool would have a smooth entrance and exit of the cut. Any burr formation was removed between the test passes.

Table 1. Cutting data used in the tests.

Parameter	Value
Cutting speed, v_c	200, 300 m/min
Feed, f_n	0.1 mm/r
Depth of cut, a_p	1.0 mm
Coolant pressure, conventional	0.7 MPa
Coolant pressure, high-pressure	5, 10, 15 MPa

Tool wear was measured several times during the tool life. A Mitutoyo tool maker's microscope was used for the measurements. According to ISO 3685 [19], the most common life measures for ceramic tools are the average and the maximum widths of the flank wear land. Depth-of-cut notch wear is said to depend on the accuracy of repeated depth settings and must therefore be excluded from the flank wear measurements. Another issue with ceramic tools is edge chipping. According to ISO 3685, this type of wear is, to a certain extent, taken into account by the maximum width of the flank wear land. Thus, the maximum width of the flank wear land VB max of 0.8 mm was chosen as a tool life criterion in this study.

3. Results and discussion

The main type of tool wear observed in the tests was flank wear and to some extent edge chipping. The notch wear was generally smaller than the flank wear and did not define the tool life. Severe notch wear is usually observed in machining of Inconel 718, but the lower hardness of Inconel 625 could explain the low notch wear. Figure 2 shows the typical type of tool wear observed in the tests.

The tool life results are shown in Table 2. In test *c* increased chipping and relatively short tool life was observed, but the other tests indicated a very high repeatability of the tool life. There was very little variation in tool life between the different cooling methods. The choice of cooling method did not significantly affect the tool life.

Table 2. Experiments and resulting tool life.

	Cutting speed (m/min)	Conventional cooling	High-pressure cooling			Tool life, (s)
			5 MPa	10 MPa	20 MPa	
a	200	x				136
b	200	x				156
c	200	x				87
d	200	x				153
e	200		x			158
f	200			x		156
g	200				x	156
h	200	x	x			168
i	200	x		x		155
j	200	x			x	167
k	300	x				66
l	300	x				66
m	300		x			67
n	300			x		71
o	300				x	71
p	300	x	x			66
q	300	x		x		70
r	300	x			x	66

The results show that there is a very large difference in tool life at high and low cutting speed. The tool life at 300 m/min is in average approximately 50 % of the tool life at 200 m/min. This implies that the volume of removed material by one cutting tool is reduced by approximately 25% when the cutting speed is increased from 200 to 300 m/min.

Good chip breaking was observed when high-pressure cooling was used, even at the lowest pressure level. When using conventional cooling, the chip was mainly long and unbroken. An example of efficient chip breaking is shown in Figure 3.

The edge chipping observed in this study is a common problem when working with brittle tools and can be accelerated by thermal cycling or shocks. Thermal conductivity of ceramics is much lower than that of the carbides. This means that heat dissipation deeper into the tool is slow and that the hot zone is localized close to the edge. When high-pressure coolant is applied, the temperature in the area around the target point drops down significantly. However, due to the low thermal conductivity the cooling effect on the cutting edge is low compared to carbide tools. As a consequence, a temperature gradient is created, which can lead to thermal cracking and can accelerate edge chipping.

Fig. 1. Experimental setup

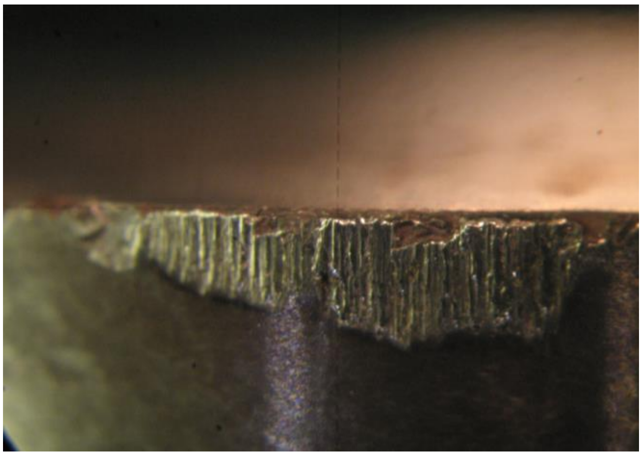

Fig. 2. Flank wear and tool edge chipping

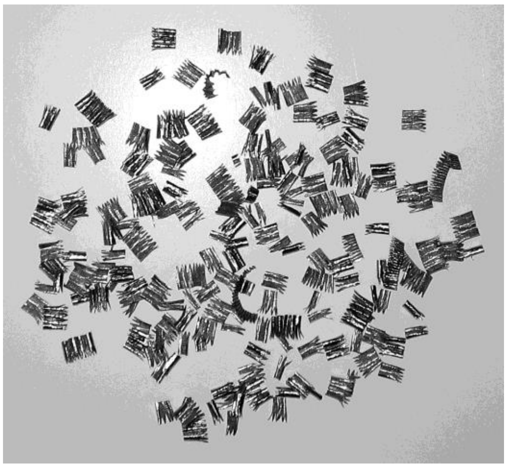

Fig. 3. Efficient chip breakage with high-pressure cooling (10 MPa).

Another possible reason for thermal cycling is the varying chip contact length [15]. At the start of its growth chip is short and is not seriously affected by the high-pressure cooling. As it gets longer, the jet acts on a larger surface area and creates a bigger bending moment. This makes the chip curl up, thus reducing its contact with the tool. Eventually the chip breaks down and the cycle repeats. As a consequence the access for the fresh coolant to the cutting edge is opened and closed in a cyclic manner. Under such conditions, crack propagation can be initiated and can eventually lead to tool failure. Ezugwu and Bonney [16] suggest that this process can be further accelerated by the jet itself, which is powerful enough to penetrate into the existing and newly created cracks and can make them propagate. The above hypothesis is partially supported by our tests. Shorter chip contact length also means that pressure from the chip is applied closer to the cutting edge and onto a smaller area, which leads to concentration of stresses close to the edge, which in turn could further accelerate edge chipping.

4. Conclusions

In this study the effect of high-pressure cooling on the performance of SiAlON-based ceramic tools in machining of Inconel 625 was investigated. The results of the study show that the use of high-pressure cooling does not increase or reduce the tool life compared to conventional cooling. The tool wear was characterized by flank wear and edge chipping. The notch wear was not significant. The high-pressure cooling contributed to excellent chip breaking.

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