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ORIGINAL ARTICLE

Effect of high-pressure cooling on life of SiAlON tools in machining of Inconel 718

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Abstract High-pressure cooling has proven to be very effective when machining with carbide inserts. Longer tool life and improved chip breaking are among the most commonly mentioned advantages. Nevertheless, this cooling method has been reported to reduce the life of ceramic tools in machining of heat-resistant alloys. The main reason for that is said to be the accelerated notch wear. Therefore, in this study, SiAlON ceramic inserts with improved resistance to notching were tested in machining of Inconel 718 under high-pressure cooling. The results were compared to conventional cooling. It turned out that, while notch wear was still slightly increased when high-pressure cooling was applied, it was no longer critical for the tool life. Flank wear, on the other hand, was reduced, which led to significantly longer tool life. The variation of the tool life appeared to be slightly less and chip breaking was considerably improved. This shows that, when used properly, high-pressure cooling can help to increase the productivity in machining of heat-resistant alloys with ceramic tools.

Keywords High-pressure cooling · SiAlON cutting tools · Inconel 718 · Tool life

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1 Introduction

Machining of heat-resistant aerospace materials, such as the nickel-based alloy Inconel 718, is characterized by low cutting speeds and, therefore, poor productivity. The main reasons for that are high hardness and low thermal conductivity of these materials. As a result, a very high temperature is generated 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 inserts can reach 1,300°C. At such temperature, cutting tools soften significantly; thus, they can be easier eroded by abrasion. In addition, heat promotes diffusion wear and can cause thermal shocks and fatigue. Therefore, to achieve a reasonable tool life, heat-resistant alloys are often machined at speeds as low as 30 to 100 m/min [2].

One way to raise the efficiency in machining of heat-resistant alloys is to use more advanced cutting tool materials. A good example is ceramics. As shown by Vigneau et al. [3], when turning Inconel 718 with alumina, cermet, and silicon nitride-based inserts, metal removal rate can be increased up to four times as compared to carbides. The reason for this is the exceptional hardness and abrasion resistance of these tool materials. Moreover, ceramics have a very high melting point; thus, they remain stable and retain their supreme properties at elevated temperatures.

Besides the desirable properties, ceramic tools also have some weaknesses. A particular concern is their sensitivity to thermal stresses. Owing to this drawback, it is sometimes recommended to use no or very small quantities of coolant when working with ceramic tools [4]. However, due to extreme temperatures generated when machining heat-resistant alloys, dry cutting can only be performed at relatively low speeds [5] and is therefore inefficient [6]. Thus, despite the improved heat resistance of ceramics tools, measures to reduce temperature in the cutting zone need to be taken.

Traditionally, large 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 cutting of heat-resistant alloys. The issue is that, in the range of temperatures developed in machining of these materials, coolants are rapidly evaporated. As a result, a steam "blanket" is created, which stops the coolant from reaching the tool–chip interface, thus rendering conventional flushing ineffective. A few alternative techniques, including internal chilling of the insert, cryogenic, CO_2, and high-pressure cooling, have been tested. The last method seems to be particularly promising.

In high-pressure cooling, cutting fluid is supplied in the form of a small jet. This "pushes" the coolant closer to the cutting edge; hence, cooling becomes more effective. Already, the early experiments performed by Pigott and Colwell [7] showed that, in rough turning of aircraft exhaust valves made in a nickel-based material, this method could increase the output per carbide tool by over 18 times. Later applications of high-pressure cooling in various machining operations confirmed the effectiveness of this method.

From the above discussion, it follows that high-pressure cooling is an effective way to reduce the temperature in the cutting zone and, therefore, leads to improved tool life. Then if the same advantage also applied to ceramic inserts, productivity in machining of heat-resistant alloys could be increased significantly. As mentioned previously, these tool materials are generally sensitive to temperature variations. Nevertheless, certain sorts of ceramics, such as alumina reinforced with SiC whiskers and SiAlON, have improved resistance to thermal shocks [8, 9]. It is therefore interesting to investigate whether these tools could be used under high-pressure cooling. A few studies involving SiC-whiskers-reinforced inserts have already been carried out and are reviewed in Section 3. In the present work, the focus was placed on SiAlON tools, which were used in machining of a heat-resistant alloy, Inconel 718, under high-pressure cooling.

2 Effect of high-pressure cooling on machining performance

The effect of high-pressure cooling has been studied from various perspectives, including its influence on friction [10, 11], cutting forces [11–16], surface finish [12–18], and surface integrity [19]. The most significant advantages of using high-pressure cooling, though, are considerably improved chip breaking and reduced temperature in the cutting zone, leading to longer tool life.

2.1 Effect on chip breaking

The most noticeable benefit of using high-pressure cooling is very efficient chip breaking. In nearly all studies that will be reviewed next, high-pressure cooling produced short chips. Under conventional cooling, the same test conditions resulted in long continuous chips, which are undesirable, especially in automated machining. Mazurkiewicz et al. [11] suggest that this improvement is due to the hydro-wedge, which is created as the focussed coolant jet penetrates between the tool's rake face and the chip. This wedge acts as a regular chip breaker, i.e., it lifts the chip up and reduces its curl radius. Eventually, the chip is broken down and is flushed away by the powerful jet.

2.2 Effect on temperature and tool life

Applying cutting fluids at high pressure significantly improves the efficiency of the cooling process. As shown by Nagpal and Sharma [12], this way, an up to 45% reduction in tool–chip interface temperature can be achieved. Similar observations have been made by Kaminski and Alvelid [20]. Due to these improvements, high-pressure cooling usually leads to significantly longer tool life.

Wertheim et al. [21] applied through-tool high-pressure cooling in grooving of Inconel 718 and a few more materials. As a result, both crater and flank wear of carbide inserts were considerably reduced. Consequently, tool life increased.

Ezugwu and Bonney [15, 18] applied high-pressure cooling in rough and finish turning of Inconel 718 with coated carbide tools. They used a number of rejection criteria, such as the level of tool wear (flank, nose, and notch), cutting edge failure, and the workpiece's surface roughness, and showed that, under the correct choice of machining and system parameters, a considerably longer tool life can be achieved.

The effect of high-pressure cooling on the performance of carbide tools has also been investigated in machining of other aerospace materials. Sørby et al. [22] used high-pressure cooling in turning of Waspaloy. This reduced the flank wear and resulted in less edge chipping. Similar effects were observed in grooving of Ti–6Al–4V [23]. Application of high-pressure cooling in turning of Ti–6Al–4V has been investigated by Machado et al. [24], Nandy and Paul [25], Nandy et al. [16], and Ezugwu et al. [26]. In all of these cases, significant reduction in tool wear, and, hence, improvement in tool life, was observed.

To explain the above-discussed improvements in tool life under high-pressure cooling, a few theories have been proposed. Kaminski and Alvelid [20] suggested that the key was the ability of the jet to break the steam barrier, which builds up when coolant gets evaporated. As a result, fresh coolant can reach the tool and can carry away the heat.

Another critical factor is the ability of the pressurized fluid to penetrate deeper into the interface between tool's flank face and the workpiece (in flank face cooling) or between the rake face and the chip (in rake face cooling). In the former case, the jet is not obstructed by the chip. Therefore, coolant can be pushed closer to the cutting edge. In rake face cooling, the chip is in the way of the jet. However, according to Mazurkiewicz et al. [11], in this case, a hydro-wedge is created. As a result, the chip is lifted up, giving access for the coolant to the cutting edge.

Lifting up of the chip has another important effect. Measurements of the width of the worn area on the rake face of the tool show that the length of the contact between the tool and the chip is reduced in high-pressure cooling [8, 16, 27]. Meanwhile, Sadik and Lindström [28] have demonstrated that reducing the chip contact length leads to a decrease in tool temperature and, consequently, to lower flank wear. This suggests that the drop in temperature, followed by improved tool life, in high-pressure cooling is at least partially due to the mechanisms provoked by the shorter chip contact length. On the other hand, Sadik and Lindström [28] observed that, when the chip contact length was reduced beyond a certain limit, both the temperature and the flank wear increased substantially. Sadik and Lindström [28] explain that, in this case, forces act on a very small area; thus, compressive stress is increased. Moreover, the reduction in the chip contact length means that the highest temperature region is "pushed" closer to the cutting edge. This causes elastic deformation of the tool. Consequently, the area of contact between it and the workpiece is enlarged, leading to increased flank wear.

Reduction in the chip contact length, followed by the concentration of stresses and shift of the highest temperature zone closer to the cutting edge, is a possible explanation for those cases where high-pressure cooling led to shorter tool life. Machado et al. [24] and Ezugwu et al. [8], for example, observed reduced life of uncoated carbide tools in turning of Inconel 901 (though some improvement was achieved at the highest cutting speed). Results presented by Sharman et al. [19] show that, in machining of Inconel 718 under high-pressure cooling, tool life was worse than, or at best equivalent to, that obtained under conventional flushing. Under some test conditions, shorter tool life in turning of Inconel 718 was also observed by Ezugwu and Bonney [15, 18].

3 Effect of high-pressure cooling on performance of ceramic tools

As discussed in the previous section, high-pressure cooling leads to more efficient chip breaking and usually extends the tool life. Despite these improvements, the number of reported studies on the application of this technique when machining with ceramic tools is scarce, and, as shown by the examples below, the results can be mixed.

Ezugwu et al. [8] experimented with high-pressure cooling in turning of Inconel 901 with SiC-whiskers-reinforced ceramic inserts. They observed that cooling at a pressure of 14 MPa enhanced chip breaking. However, it generally led to reduced tool life as compared to conventional flushing. The reason for this was said to be the accelerated notch wear.

Analogous results were achieved by Öjmertz and Oskarson [31], who 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 was observed as the pressure was raised from 80 to 360 MPa.

A similar work was done by Ezugwu and Bonney [29], who 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 also observed that jet cooling caused severe notching and, therefore, led to shorter tool life as compared to conventional flushing.

Ezugwu et al. [30] achieved slightly more promising results under finishing conditions. In general, the tool life improved at coolant pressures of 11 and 15 MPa. At 20 MPa, though, it dropped significantly due to the accelerated notch wear. Tool life was also shorter at 11 MPa when the speed was increased to 300 m/min.

According to Ezugwu and Bonney [29], the reduction in the life of ceramic tools that has been observed when high-pressure cooling was applied could be caused by hydrodynamic erosion. They suggest that, when the jet hits the tool, it comes to a sudden rest and builds a stagnation pressure. To release it, coolant tries to escape through the depth-of-cut region. This way, small abrasive particles caught in the fluid are flushed away at a high velocity, which causes severe wear in this region. Öjmertz and Oskarson [31], on the other hand, suggest that cooling at a high pressure could reduce the temperature of the workpiece below a certain threshold. This would increase its strength and would result in a higher tool contact pressure. Consequently, the wear would intensify, leading to shorter tool life.

4 Hypotheses

The review of the previous work on high-pressure cooling shows that this technique is very effective when machining with carbide tools but, in general, has a negative influence on the performance of ceramic inserts. It should be emphasized, however, that, in the studies reported so far, only ceramics based on alumina reinforced with SiC-whiskers have been used under high-pressure cooling, while tools made in SiAlON have not been tested. Therefore, performance of SiAlON inserts in machining of Inconel 718 under high-pressure cooling will be investigated in this study.

Since tool life is one of the main considerations in machining economics, the main goal of this study is to check whether the application of high-pressure cooling could prolong the life of SiAlON tools. Thus, the central hypothesis to be tested is:

$$H_{0_1} : \mu_{\mathrm{hpc}} = \mu_{\mathrm{conv}} \quad \text{versus} \quad H_{1_1} : \mu_{\mathrm{hpc}} > \mu_{\mathrm{conv}}, \tag{1}$$

where μ is the mean tool life and indexes hpc and conv stand for high-pressure and conventional cooling, respectively.

In addition, it is important to note that it is now commonly accepted that tool life is a stochastic rather than a deterministic quantity (e.g., see [32]). As a consequence, the actual tool life rarely matches the predicted values. This leads to conservative replacement strategies. According to Wiklund [33], only 50–80% of the expected life is typically used. As a result, tool consumption and related replacement costs are higher than necessary, as are the losses in terms of the productive time. For these reasons, it is important to investigate not only the mean, but also the variance of the tool life. Demonstrating that it could be reduced by applying high-pressure cooling would mean that, this way, the service length of cutting tools would become more predictable, which can be expected to have a substantial economical effect. Such outcome would be reasonable considering the fact that a focused high-pressure jet is more stable than a low-pressure stream and should therefore result in a more stable cooling process. Improved chip breaking should also add stability to the cooling process, as it would not be obstructed by long chips. Hence, the second hypotheses to be tested in this study is:

$$H_{0_2} : \sigma^2_{\mathrm{hpc}} = \sigma^2_{\mathrm{conv}} \quad \text{versus} \quad H_{1_2} : \sigma^2_{\mathrm{hpc}} < \sigma^2_{\mathrm{conv}}, \tag{2}$$

where σ^2 is the variance of the tool life, while indexes hpc and conv stand for high-pressure and conventional cooling, respectively.

5 Experimental work

In order to test the above hypotheses, machining experiments were performed. For this purpose, 20 SiAlON ceramic inserts and an Inconel 718 workpiece were prepared. As mentioned in Section 1, very high temperatures have been recorded when machining this material. Therefore, it was decided that, in order to maximize the extraction of heat, high-pressure cooling should be used in combination with conventional flushing. This technique will be referred to as high pressure-assisted cooling in the following text. The physical configuration of the experimental cooling system and the test conditions are described next.

5.1 Experimental set-up

Cutting experiments were carried out with a Hessapp DV80 lathe (see Fig. 1). The machine is equipped with an auxiliary pump, which delivers pressurized (up to 40 MPa) cutting fluid to the outlet on the tool turret. From this point, coolant is transported via a copper tube to a custom-made insert clamp with internal channels (see Fig. 2). Such system is very rigid; thus, the direction and the target point of the jet do not change as a result of the reactive forces. This was expected to add stability to the cooling process, hence, to minimize

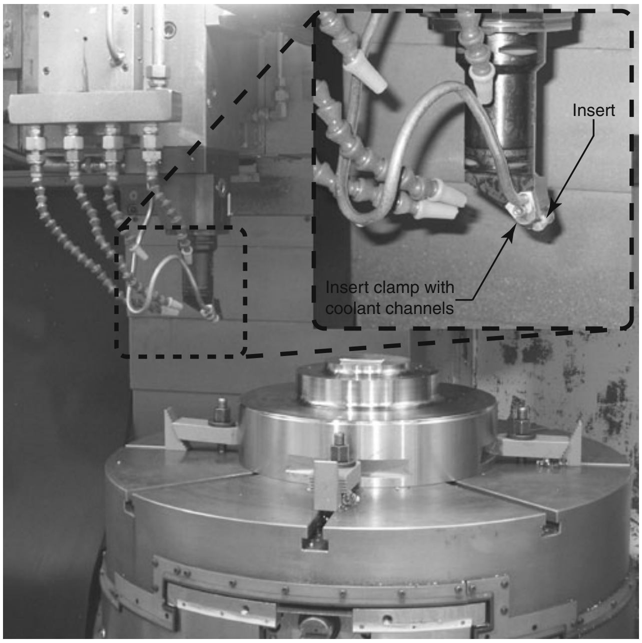


Fig. 1 Experimental set-up

thermal variation, which ceramic tools are known to be sensitive to.

Since ceramic tools are also known to be brittle, special measures were taken to minimize the occurrence of mechanical shocks. Workpiece was securely clamped on the pallet, and a few millimeters of material were removed from its sides to compensate for the centring error. Moreover, the tool was programmed to follow an arc-shaped trajectory at the start and the end of each cut. This way a smooth entrance to and exit from the workpiece was achieved.

Cutting conditions used in these experiments are typical for semi-rough machining of Inconel 718 with ceramic tools. They were kept constant and were the same during both high pressure-assisted cooling and the control tests, where only conventional cooling was applied. This was done in order to assure that the only source of possible difference in the observed results was the cooling method. For further experimental details, please see Table 1.

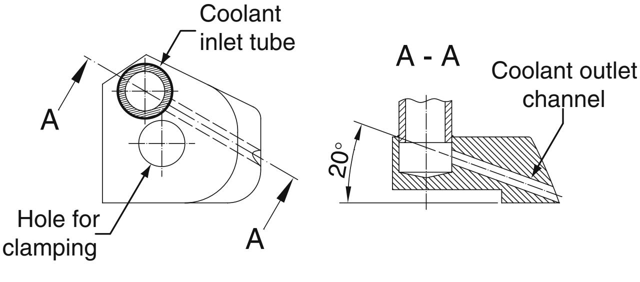


Fig. 2 Insert clamp with coolant channels

Table 1 Experimental conditions

Workpiece	Material	Inconel 718
	Hardness	33 HRC
	Shape	Solid cylinder
	Diameter	400 mm
	Height	150 mm
Tool	Material	SiAlON
	Insert type	RCGX 120700 E
	Holder type	PCLN
Cutting data	Operation	Facing
	Speed, v_c	300 m/min
	Feed, f_n	0.2 mm/rev
	Depth of cut, a_p	1.0 mm
Cooling	Coolant	Emulsion, 4%
	Control method	Flooding at 0.7 MPa
	Test method	Flooding + High pressure cooling at 20 MPa

5.2 Procedure

Test inserts were labelled with numbers from 1 to 20. Half of them were selected for high pressure-assisted cooling tests. The rest were controls and were used for machining under conventional cooling alone.

The experiment was carried out in multiple tool paths divided into several cuts. To make sure that the conditions in each of the test cuts were approximately the same, each path of the tool was executed in three stages.

Stage 1. The previous experience has showed that a burr tends to form on the outer edge of the cylindrical workpiece. As a result, the tool sustains a shock at the beginning of the next path. To avoid this, a dummy tool was used to remove the burr.

Stage 2. At this stage, the test tools were used. Due to the size of the workpiece, each path was split into three parts, resulting in three cuts of equal duration. In order to avoid any possible bias due to inhomogeneity of workpiece material or scale that could have formed on its surface during the previous tool path, experiments were *randomized*. To accomplish that, a number from 1 to 20 was drawn to select the tool. After completing the cut, which, on average, took 35 s, the insert was removed from the tool holder and the wear was measured with a Mitutoyo toolmaker's microscope. Then, a new random number was drawn to determine the tool to be used in the next cut.

Stage 3. After completing the third cut, a dummy insert was used again to remove a few millimeters of material. The reason for this last operation was to avoid the contact between the test tool and the core that formed in the center of the workpiece.

Having finished one path, the tool was lowered by the amount of the depth of cut, i.e., by 1 mm, and the three-stage procedure was repeated again. This work was continued until each insert had performed four cuts. By that time, the wear on all test tools had reached the limit to be defined in the following section.

5.3 Tool life criterion

According to ISO 3685 [34], the most common life measures for tools of ceramics are the average and the maximum width of the flank wear land. Depth-of-cut notch wear, which is often mentioned to be an issue when machining nickel-based alloys with ceramic tools, is said to depend on the accuracy of repeated depth settings and must therefore be excluded from the flank wear measurements. Another common problem with ceramic tools is edge chipping. According to ISO 3685 [34], to a certain extent, this type of wear is taken into account by the maximum width of the flank wear land, which, for the latter, is the recommended measure when edge chipping is expected. Thus, the maximum width of the flank wear land *VB* max of 0.6 mm was chosen as the tool life criterion in this study.

6 Results

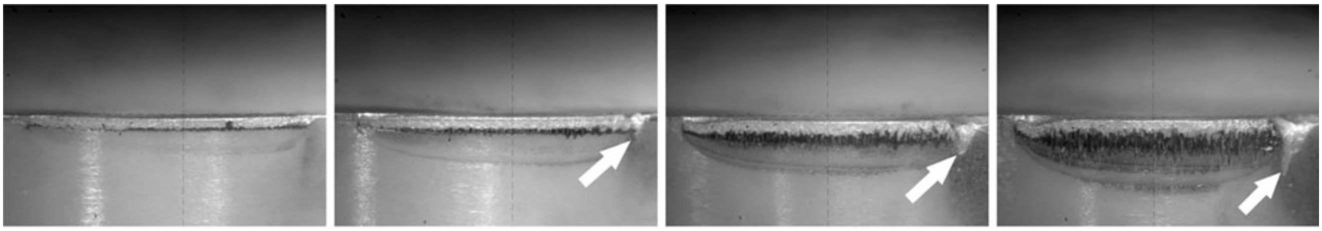
This section presents the results of the experiments. It starts with a discussion about the observed wear of SiAlON inserts under conventional and high pressure-assisted cooling. Coming out from this, tool lives are derived and the hypotheses postulated in Section 4 are tested. In addition, the observed effect of high-pressure cooling on chip breaking is briefly discussed.

6.1 Tool wear

As mentioned in Section 3, notch wear at the depth-of-cut region is usually the most serious issue when machining nickel-based alloys with ceramic tools under high-pressure cooling. In our experiments, notch wear only became significant at later stages of the cutting process (see Fig. 3). In general, it was more intense under high pressure than under conventional cooling. In the latter case, the maximum length of the depth-of-cut mark was 0.59 mm, and in case of high-pressure cooling, it was 0.82 mm. Such level of notch wear was considered to be within reasonable limits, hence, not critical for the tool life.

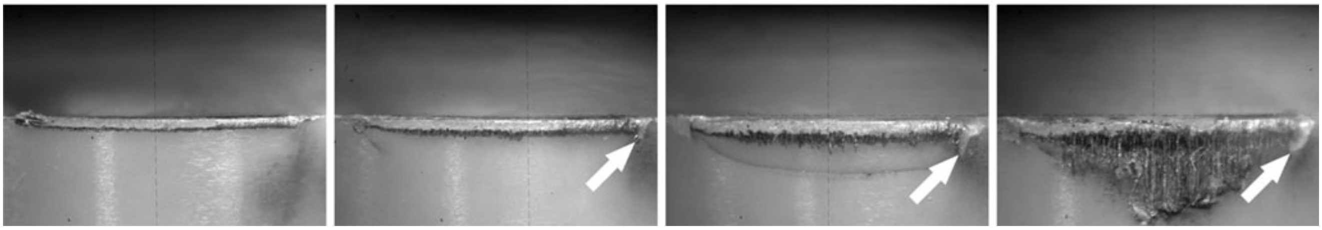
Flank wear was clearly visible from the first cuts (see Fig. 3) and was increasing steadily as machining continued. As illustrated in Fig. 4, its rate was slightly higher under conventional cooling, and the gap was growing as the cutting progressed further. Moreover, in case of conventional cooling, there was more work material being welded to the tool. This attached layer

High pressure-assisted cooling



after 35 seconds after 70 seconds after 105 seconds after 140 seconds

Conventional cooling



after 35 seconds after 70 seconds after 105 seconds after 140 seconds

Fig. 3 Tool wear under high pressure-assisted and conventional cooling

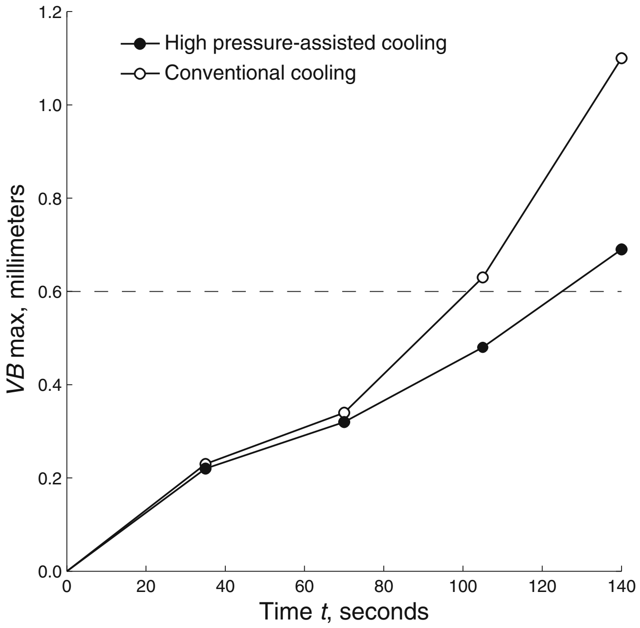


Fig. 4 Development of flank wear land (each point represents the average of 10 observations)

was carefully removed in order to expose the flank face of the tool and to measure the true amount of wear.

6.2 Tool life

In Section 5.3, the critical width of the maximum flank wear land was set at 0.6 mm. The time when this limit was reached was determined by interpolating between the two nearest experimental points. The results together with the basic sample statistics are shown in Table 2 (note that the tool lives seen here are typical for semi-rough machining of Inconel 718 with ceramic inserts). These data will now be used to test the hypotheses postulated in Section 4. Since most of the commonly used statistical methods are based on the assumption of equal variances, we will test H_{0_2} first, and will then proceed with H_{0_1}.

6.2.1 *Comparison of variances*

The data shown in Table 2 suggest that the variance was lower when high-pressure cooling was applied. However, this difference could be due to random rather than systematic causes. To check this, let us assume that the two data samples came from two normal distributions. Then, we can verify the validity of hypothesis H_{0_2} by applying the F test.

Table 2 Observed tool lives (in seconds)

	High pressure-assisted cooling	Conventional cooling
Tool life, T	136	115
	134	110
	126	108
	140	112
	113	101
	131	109
	133	90
	128	83
	117	108
	129	107
Sample mean, $\overline{T}$	129	104
Median, $\widetilde{T}$	129.9	108.2
Sample variance, s^2	69	107

Given our experimental data, the statistic of the test is $f_0 = s^2_{\text{hpc}}/s^2_{\text{conv}} = 0.6449$. We would reject H_{0_2} if

$$f_0 < f_{1-\alpha,n_{\text{hpc}}-1,n_{\text{conv}}-1}, \tag{3}$$

where n is the sample size and α is the significance level. In our case, $n_{\text{hpc}} = n_{\text{conv}} = 10$, and we chose α to be 0.05. Thus, we would reject H_{0_2} if $f_0 < f_{0.95,9,9}$. By making use of the identity $f_{1-\alpha,u,v} = 1/f_{\alpha,u,v}$ and by looking up the tables for the F distribution, we find that $f_{0.95,9,9}$ is approximately equal to 0.3145. Since this number is less than our test statistic, we cannot reject H_{0_2}, i.e., we do not have enough evidence to claim that the variances under the two types of cooling are different. In fact, the p value in this case is 0.524. Thus, it is very likely that the cause of the observed differences was random variation.

Despite the fact that we cannot reject H_{0_2}, it should be mentioned that, based on the collected data, standard deviation of the tool life was approximately 1.25 times larger in case of the conventional cooling. However, this estimate is based on samples of size 10, which are small from a statistical point of view. Given that, we can read from the operating curves for the F distribution (found in statistical handbooks) that, even if the difference revealed by the experimental data represented the true difference between the standard deviations, which would imply that the alternative hypothesis H_{1_2} was true, the probability of accepting H_{0_2} would still be more than 80%.

In the above calculations, we have assumed that the data sets were normally distributed. Due to its simplicity and symmetrical shape, normal distribution is sometimes used to model the life of cutting tools (e.g., see [32, 35–37]). Nevertheless, there are a couple issues with this assumption. First, the normal distribution allows for negative values and is therefore not a realistic life model. Second, careful examination of the data shows that, even if it was a viable model, the normal distribution does not describe the tool lives observed under the conventional cooling well. Therefore, to check whether the conclusion drawn above is correct, we have dropped the normality assumption and applied the Levene's test.

The calculated test statistic is $W = 0.0216$ (the calculations are cumbersome and therefore not shown here). We would reject H_{0_2} if

$$W > f_{\alpha,k-1,N-k}, \quad (4)$$

where N is the total number of data points and k is the number of subgroups. In our case, $N = 20$ and $k = 2$. Then, if we kept α at 0.05, we would reject H_{0_2} if $W > f_{0.05,1,18}$. Looking up the tables for the F distribution, we find that $f_{0.05,1,18}$ is approximately equal to 4.4139. Since this value is much grater than our test statistic, we cannot reject H_{0_2}, i.e., we do not have enough evidence that the variances under the two types of cooling are different. The p value for this test is 0.885 and is even greater than under the normality assumption. Thus, it is very likely that the differences were due to the random variation.

6.2.2 Comparison of means

In the previous section, we concluded that the normal distribution was not an appropriate model for our experimental data. Thus, we cannot use the t test to compare the means, i.e., to test the hypothesis H_{0_1}. An alternative solution is to apply the non-parametric Wilcoxon (Mann–Whitney) test for the medians $\widetilde{T}_{\text{hpc}}$ and $\widetilde{T}_{\text{conv}}$.

The test statistic W_{hpc} is the sum of ranks for the tool lives observed under high pressure-assisted cooling and is equal to 154. The probability of obtaining such a high number, given that $\widetilde{T}_{\text{hpc}} = \widetilde{T}_{\text{conv}}$, is 0.0001. In other words, it is very unlikely that experimentally collected data would show such a difference if the true medians were equal. Indeed, the 95% confidence interval for $\widetilde{T}_{\text{hpc}} - \widetilde{T}_{\text{conv}}$ is (16.84, 31.57). Based on these calculations, we can reject H_{0_1} in favor of H_{1_1}, i.e., we can conclude that the life of SiAlON ceramic tools seems to be longer when high-pressure cooling is applied.

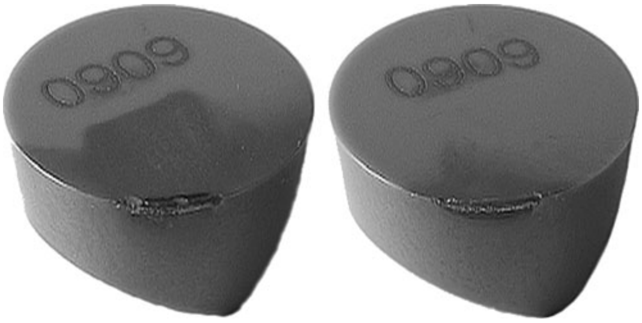

Conventional cooling High pressure-assisted cooling

Fig. 5 Effect of cooling method on chip contact length


Conventional cooling High pressure-assisted cooling

Fig. 6 Effect of cooling method on chip breaking

6.3 Chip breaking

Besides affecting the tool wear, high-pressure cooling had a considerable influence on chip flow. As can be seen in Fig. 5, the discolored area, i.e., the region where the chip was in contact with the tool, covers nearly half of the rake face of the insert used under conventional cooling, while on the tool used under high pressure-assisted cooling, there is almost no discoloration. This shows that, in the latter case, the chip was curling up much earlier. As a consequence, it was broken into shorter segments. This is illustrated in Fig. 6. As can be seen here, chips produced under high-pressure cooling were very short, needle-like, while under conventional flushing, they were long and tubular.

7 Discussion

In this study, machining of a heat-resistant aerospace material, Inconel 718, with SiAlON ceramic inserts under high-pressure cooling was tested. The presented overview of earlier research shows that the latter technique usually leads to longer tool life and significantly improves chip breaking. When applied in machining of nickel-based alloys with ceramic tools, however, high-pressure cooling has been reported to accelerate notch wear and, therefore, to lead to reduced tool life. To overcome this problem, in this study, ceramic tools with improved resistance to notching were used, and special measures were taken to minimize the occurrence of thermal and mechanical shocks.

The above set-up proved to be effective. Even though notch wear was still more intense under high pressure-assisted cooling, it remained within reasonable limits and was not critical for the tool life. Flank wear, on the other hand, was reduced as a result of high-pressure cooling. Therefore, tool life was significantly longer.

The reduction in flank wear and, consequently, the improvement in tool life is the result of more efficient cooling. As indicated by the observed reduction in chip contact length, when applied at a high pressure, coolant overcomes the resistance of the chip, lifts it up, and penetrates closer to the cutting edge, where the highest temperature occurs. Moreover, the speed of the coolant flow is much higher under high-pressure cooling, which for the dissipation of heat, is more rapid. Combination of these two factors leads to more efficient cooling of the cutting edge. As a consequence, the intensity of wear processes is reduced. On the other hand, rapid cooling can lead to thermal cracking, followed by micro chipping. This effect can be expected to be pronounced in the depth-of-cut region, where coolant has a direct contact with the heated cutting zone. For this reason, the rate of cooling, hence, the likelihood of thermal cracking and micro chipping, should be particularly high here, which would explain the observed increase (though not very significant) in notch wear.

The results of this study also suggest that the variance of the tool life might be reduced by applying high-pressure cooling. This would be reasonable, considering the fact that, in such case, cooling process is not obstructed by long chips and is probably more stable. However, we did not have enough statistical evidence to support this claim, despite the fact that the sample sizes that we used in our experiments are rather big for this type of study.

8 Conclusions

The results achieved in this study show that, when the machining process is properly designed, high pressure-assisted cooling can help to extend the life of SiAlON ceramic tools, hence, reducing the costs in machining of heat-resistant alloys. Alternatively, the cutting speed could be increased, which would make the process more productive. Moreover, high pressure-assisted cooling significantly improved chip breaking. Since long chips can scratch the workpiece and can block the disposal equipment, this advantage is important, especially in unattended machining.

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