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Improving tool life using cryogenic cooling

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ABSTRACT

The major needs in machining are high material removal rate, good work surface finish and low tool wear. These objectives can be achieved by reducing tool wear using proper cooling system of the tool during machining. In the present work a tool has been modified to apply liquid nitrogen as coolant through a hole made in the tool so that liquid nitrogen can be directly applied to the machining zone during machining of stainless steel with carbide tools coated with titanium carbonitride. It was found that the tool life increases more than four times by applying liquid nitrogen using the modified tool. Application of this cryogenic cooling was found to be more effective at higher cutting speeds. It was also observed that cryogenic cooling is efficient at a higher feed rate rather than a higher depth of cut.

1. Introduction

The most emerging needs of the modern metal cutting operation are to increase the material removal rate with better surface finish and high machining accuracy. In metal machining process, the condition of the cutting tools plays a significant role in achieving consistent quality and also for controlling the overall cost of manufacturing. Machining of harder materials using existing conventional techniques is uneconomical as the machining process results high tool wear and takes longer time. In some cases, tools wear out very rapidly mainly during machining of high strength and metal matrix composites (MMC). Also, in some cases, chemical composition as well as microstructures of the materials to be machined may be altered due to the rise of temperature in the machining environment. The main problem caused during machining is due to the heat generation and the high temperature resulted from heat. The heat generation becomes more intensified in machining of hard materials because the machining process requires more energy than that in cutting a low strength material. Additionally, the thermal conductivity of the advanced materials such as silicon nitride (about 13 W/m °C), titanium alloy (about 15 W/m °C) and Inconel (about 11 W/m °C) are much lower than those commonly used alloy steels. As a result, the cutting temperatures in the tool and the workpiece rise significantly during machining of these advanced materials.

One approach to enhance the machining performance in cutting hard-to-cut materials is hot machining (Konig et al., 1990; Kitagawa and Maekawa, 1990). It has been reported that tool life can be increased much by hot machining of manganese steel (Tosun and Özler, 2002). Kitagawa and Meakawa found that machining by softening the workpiece is more effective way than strengthening the tool (Kitagawa et al., 1988). 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.

The most practical and effective way to enhance the machining performance in cutting difficult-to-cut materials is to reduce cutting temperature (Evans, 1991a; Wane et al., 1996; Itoigawa et al., 2006). High-pressure jet cooling is an effective way of reducing cutting temperature. A longer tool life was

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observed by Ezugwu et al. (Ezugwu et al., 2007) when machining Ti–6Al–4V with high-pressure coolant supplies and the recorded surface roughness values were found to be below the tool rejection criteria. But during machining of Ti–6Al–4V the performance of CBN tools in terms of tool life was found to be poor compared to uncoated carbide tools and probably it is due to rapid notching and excessive chipping of the cutting edges (Ezugwu et al., 2005a). Machining of Incol 718 with whisker reinforced ceramic tools gave better performance in terms of tool life under high-pressure coolant supplies compared to conventional coolants (Ezugwu et al., 2005b; Ezugwu and Bonney, 2004). Seven hundred and forty percent improvement of tool life was reported at a coolant pressure of 203 bar and a cutting speed of 50 m/min. Tool life was found to increase with increase of coolant supply pressure. It was reported that the high-pressure coolant injection technique not only reduces cutting forces and cutting temperature, but also reduces the consumption of cutting fluid by 50% (Alexander et al., 1998).

Though high-pressure coolant supply exhibits a significant improvement in tool life and work surface finish, it has some drawbacks. Conventional coolants contain different chemicals that may be responsible for water pollution and soil contamination if disposed without required treatments. Proper rules are to be followed for handling and disposal of used coolants. High-pressure coolant supply also requires extra floor space, chilling and recycling of coolants (Dhar et al., 2002). To eliminate these limitations, cryogenic cooling is getting popularity. Application of cryogenic cooling gives substantial benefit on tool life, surface finish and dimensional deviation by reduction in cutting zone temperature and favorable chip–tool interface (Dhar and Kamruzzaman, 2007; Dhar et al., 2001; Paul et al., 2001). Investigations were done on tool wear during machining of Ti–6Al–4V alloy using uncoated carbide cutting tool inserts under dry, wet and cryogenic environments (Venugopal et al., 2007). A substantial improvement in tool life was obtained under cryogenic cooling compared to dry and wet machining in all the machining trials undertaken.

Hong et al. (Hong et al., 2001) introduced a new technique of application of cryogenic coolant during machining of Ti–6Al–4V. They designed a special micro-nozzle for application of liquid nitrogen. Liquid nitrogen was introduced through the gap between the chip breaker and the rake surface. The new technique provides an effective way of cooling the tool using very low flow rate of nitrogen. Tool life was reported to enhance five times to that using emulsion cooling. An innovative and economical dispensing method of applying cryogenic coolant was introduced by Hong and Ding (Hong and Ding, 2001). Cutting temperatures were theoretically estimated by finite element method and the influence of cutting speed was analyzed. They were experimentally verified using the thermocouples imbedded at the carbide insert. They found that cooling approaches in order of effectiveness (worst to best) are: dry cutting, cryogenic tool back cooling, emulsion cooling, precooling the workpiece, cryogenic flank cooling, cryogenic rake cooling and simultaneous rake and flank cooling. Investigations carried out by Wang and Rajurkar (Wang and Rajurkar, 2000) on the effectiveness of cryogenic cooling during machining of advanced ceramics by CBN tools and titanium alloys, Inconel alloys and titanium with cemented carbide tools. It was observed that hot-strength and hot-hardness of the tool remain high and the temperature-dependent tool wear reduces significantly.

Table 1 – Approximate chemical composition of SUS 304 stainless steel (%)

Chromium	18–20
Nickel	8–10.5
Carbon	0.08
Silicon	1
Manganese	2
Phosphorus	0.04
Sulfur	0.03

Table 2 – Physical properties of SUS 304 stainless steel

Yield strength (MPa)	206
Tensile strength (MPa)	516
Elongation (%)	40
Percentage reduction of area (%)	60
Hardness (HB)	187
Thermal conductivity (W/m K)	17–50

However, more work is needed to explore the potentiality of cryogenic cooling during machining advanced materials. This paper describes a new technique to apply liquid nitrogen coolant on the machining zone and its effect in turning of SUS 304 stainless steel.

2. Methodology

In the present study stainless steel SUS 304 was used as the work material. The length and diameter of the workpiece were 500 and 100 mm, respectively. Before the experiments, a layer of 2 mm was removed in order to eliminate the effect of any surface defect. The chemical compositions and the physical properties of the work material are shown in Tables 1 and 2, respectively. The tool used in the investigation was of grade AC 2000, coated with TiCN. The experiments were conducted on a lathe machine, model Harrison M390. The cutting parameters employed are shown in Table 3.

The tool, specially modified for cryogenic cooling is shown in Fig. 1. As shown in the figure, the insert 2 was fixed to the tool holder 5 by a threaded screw 8. The screw was tightened by an alen key using the hexagonal slot 1 of the screw head. Liquid nitrogen is passed into the threaded hole 4 of the tool body 5. From the tank, liquid nitrogen was passed into the hole 4 through a hose pipe and a specially made adapter. The liquid nitrogen proceeds to the expanding chamber 7 through the threaded hole 4 and the small hole 3. In the chamber 7, liquid nitrogen expanded and transformed into gaseous stage at low temperature and comes out through the small hole 6, made just beneath the insert. Thus the insert was cooled by liquid nitrogen. Stainless steel was machined with both

Table 3 – Machining parameters

Cutting speed (m/min)	100, 150, 200, 250
Feed rate (mm/rev)	0.05, 0.1
Depth of cut (mm)	0.5, 1

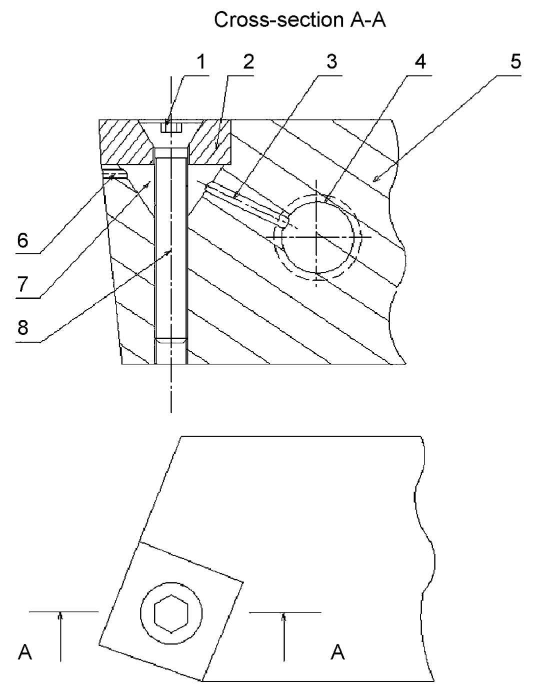

Fig. 1 – Details of the tool for cryogenic cooling.

conventional coolant and liquid nitrogen. Kutwell 40 soluble oil was used as the coolant during conventional machining. The mixing ratio of the oil to water was 5:95. After machining for certain machining time the flank wear of the insert was measured periodically using Mitutoyo Hisomet II optical microscope.

3. Results and discussions

The tool life at different cutting speeds with conventional cooling and cryogenic cooling is shown in Fig. 2. The results show that cryogenic cooling enhances tool life. Tool life with a cutting speed of 100 m/min (depth of cut and feed rate are 0.5 mm and 0.1 mm/rev, respectively) using conventional coolant is 13.45 min, where for the same cutting conditions the life is 57.45 min in cryogenic cooling. It shows that the application of cryogenic coolant has increased the tool life by 4.27 times. Again, at a higher cutting speed of 250 m/min tool lives with conventional coolant and cryogenic cooling are 22.5 and 4.62 min, respectively with the same feed rate and depth of

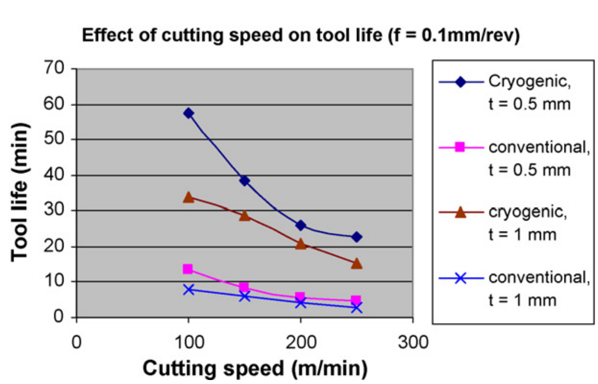

Fig. 2 – Tool life at different cutting speeds (f = 0.1 mm/rev).

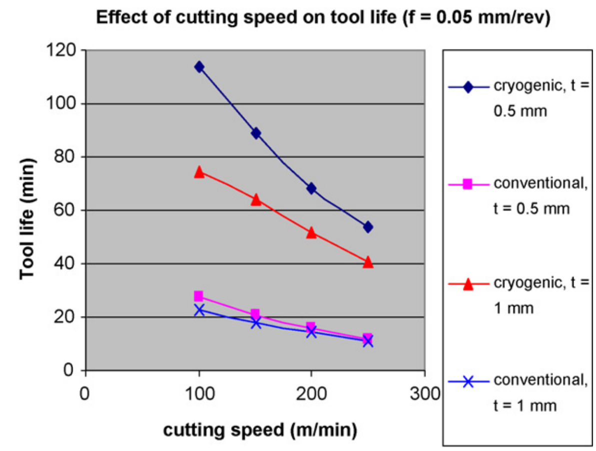

Fig. 3 – Tool life at different cutting speeds (f = 0.05 mm/rev).

cut. This shows an increase of tool life by 4.87 times. It can be observed that tool life at a higher depth of cut is substantially low compared to that at a low depth of cut. For a cutting speed of 200 m/min, tool lives for cryogenic cooling and conventional cooling are 20.7 and 4.2 min at a depth of cut of 1 mm, whereas the same are 25.92 and 5.4 min at a depth of cut of 0.5 mm.

Fig. 3 illustrates the tool life at different cutting speeds and depths of cut at a feed rate of 0.05 mm/min. Comparing the results illustrated in Fig. 3 with those in Fig. 2 it can be concluded that tool life at a lower feed rate is much higher than that at a higher feed rate. For example, tool life with cryogenic machining at a cutting speed of 100 m/min and a depth of cut of 0.5 mm is 57.43 min at a feed rate of 0.1 mm, where it is 114 min at a feed rate of 0.05 min/rev, at the same cutting speed and depth of cut, which shows an increase of tool life of almost two times. At a higher feed rate the chip thickness is increased and more heat is generated, which reduces the hardness of the tool material resulting rapid tool wear (Venugopal et al., 2007). At a higher cutting speed, the effect of reducing depth of cut shows stronger effect towards increasing tool life. For example, during machining with conventional coolant at a depth of cut of 1 mm, due to reduction of feed rate from 0.1 to 0.05 mm/min, tool life increases to 2.4, 2.59, 2.62 and 3.66 times at cutting speeds of 100, 150, 200 and 250 m/min, respectively.

Fig. 4 summarizes the benefits of cryogenic cooling in terms of tool life. The curves illustrate the percentage increase in tool life at different cutting conditions. Heat generation during machining takes place as a result of plastic deformation of metal at the shear zone, due to friction of the chip on the tool rake face and due to friction between the tool flank and the workpiece. It has been reported that energy consumption in turning is largely converted into heat (Trent and Wright, 2000). Most of the heat energy is carried away by the chip, a little amount is absorbed by the surroundings and rest of the heat is absorbed by the tool and the workpiece. The workpiece material used is stainless steel and its thermal conductivity is low compared to plain carbon steels. As a result, the temperature at the chip–tool interface rises rapidly. Moreover, at a higher cutting speed more heat is generated and consequently at the machining zone temperature rises to a very high level. The application of cryogenic coolant, therefore, can remove

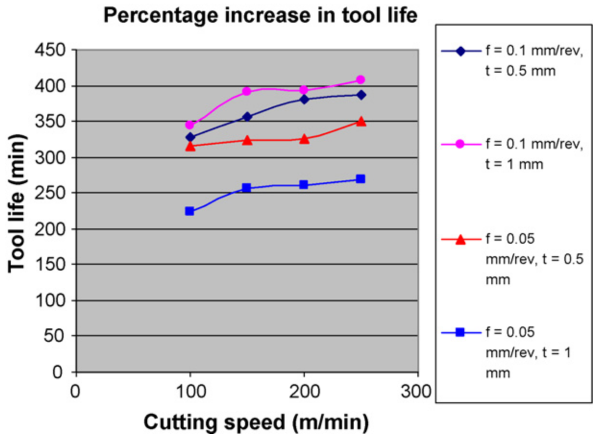

Fig. 4 – Percentage increase in tool life at different cutting speeds.

more heat from the machining zone. The application of cryogenic coolant is seen to be more effective at a higher cutting speed.

It can be seen from Fig. 4 that percentage increase in tool life for all cutting speeds and at a feed rate of 0.1 mm/min is higher than that at a feed rate of 0.05 mm/min. In other words, cryogenic cooling is more effective at higher feed rates rather than at higher depths of cut. The effect of feed rate is much stronger than the effect of depth of cut on heat generation. Consequently, more heat is generated at a higher feed rate and cryogenic cooling is more effective at a higher feed rate than that at a higher depth of cut. It was reported that cryogenic cooling reduces the cutting temperature at high cutting speed (Evans, 1991b) without polluting the environment.

Fig. 5 shows the SEM image of the flank wear after a machining time of 2 min with conventional coolant at a cutting speed, feed and depth of cut of 250 m/min, 0.5 mm/rev and 1 mm, respectively. The image shows extensive wear of the flank as well as the face and this is due to heavy cutting conditions. The flank surface suffered from attrition and abrasion wear. A crater wear is seen on the tool rake face that is

Fig. 5 – Flank wear after 2 min of machining with conventional coolant ($v = 250$ m/min, $f = 0.1$ mm/rev and $t = 1$ mm).

Fig. 6 – Flank wear after 2 min of machining with cryogenic coolant ($v = 250$ m/min, $f = 0.1$ mm/rev and $t = 1$ mm).

Fig. 7 – Flank wear after 3 min of machining with conventional coolant ($v = 200$ m/min, $f = 0.1$ mm/rev and $t = 0.5$ mm).

caused by adhesion and diffusion due to high temperature. But Fig. 6 shows that a little wear took place on the flank and face of the tool while using cryogenic coolant after a machining time of 2 min under the same cutting conditions. The cutting edge suffers minor micro-chipping for high cutting speed.

Fig. 7 shows the flank wear of the tool after a machining time of 3 min with conventional coolant while Fig. 8 shows the same for cryogenic coolant under the same machining conditions ($v = 200$ m/min, $f = 0.1$ mm/rev and $t = 0.5$ mm). Fig. 8 shows a little flank wear in cryogenic cooling. Less abrasion and attrition wear is observed at the flank surface as compared to Fig. 6 ($v = 250$ m/min) because of lower cutting speed ($v = 200$ m/min). Fig. 7 shows an extensive flank wear during machining with conventional coolant. Flank wear is caused by abrasion. Micro-cracks are also observed on the cutting edge.

Fig. 9 illustrates the flank wear of the tool after 20 min of machining with conventional coolant while Fig. 10 shows the same for cryogenic cooling under the same cutting conditions ($v = 100$ m/min, $f = 0.05$ mm/rev and $t = 0.5$ mm). Fig. 10 shows a very little flank wear after a machining time of 20 min with cryogenic coolant. Minor abrasive wear can be observed on

Fig. 8 – Flank wear after 3 min of machining with cryogenic coolant (v = 200 m/min, f = 0.1 mm/rev and t = 0.5 mm).

Fig. 9 – Flank wear after 20 min of machining with conventional coolant (v = 100 m/min, f = 0.05 mm/rev and t = 0.5 mm).

Fig. 10 – Flank wear after 20 min of machining with cryogenic coolant (v = 100 m/min, f = 0.05 mm/rev and t = 0.5 mm).

the tool flank; the cutting edge shows micro-cracks. But Fig. 9 shows a considerable flank wear after the same machining time using conventional coolant. Abrasion marks are observed on the tool flank and the cutting edge suffers from cracks due to prolonged machining.

Micrographs in Figs. 5–10 clearly show that tool wear is substantially reduced by the application of cryogenic coolant compared to conventional emulsion coolant. Conventional coolants cool the workpiece and the tool in a bulk, but cannot cool the chip–tool interface (Dhar and Kamruzzaman, 2007). Moreover, at a high cutting speed, when the chip moves at a higher speed on the tool face, a conventional coolant cools the chip first and does not get enough time to cool the cutting edge by heat conduction. But in the present study, liquid nitrogen is introduced directly to the machining zone that cools the cutting edge effectively and thus reduces tool wear.

4. Conclusions

(1) The modified tool used for applying cryogenic coolant provides an effective means for cooling the cutting edge during machining operation.
(2) The application of cryogenic coolant using the modified tool can increase tool life to more than four times.
(3) At a higher cutting speed cooling rate by conventional coolant cannot cope with the heat addition to the chip–tool interface. As a result, application of cryogenic coolant was found to be more effective at a higher cutting speed.
(4) At a higher feed rate chip thickness is higher; plastic deformation at the shear zone takes place at a faster rate generating more heat. Therefore, cryogenic cooling is more effective at a higher feed rate rather than at a higher depth of cut.
(5) For all the machining trials the tool flank suffered attrition and abrasion wear and micro-cracks were observed on the cutting edge during machining with conventional coolant. During machining at a high cutting speed the tool face showed crater wear.
(6) While machining at a lower cutting speed and using cryogenic coolant, very little wear was observed on the tool flank. However, at a high cutting speed the cutting edge suffered from micro-cracks in addition to minor flank wear.

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