Int J Adv Manuf Technol (2002) 20:83–91
Ownership and Copyright

The International Journal of
Advanced Manufacturing Technology

Effect of High-Pressure Coolant on Machining Performance

A. Senthil Kumar, M. Rahman and S. L. Ng
Department of Mechanical Engineering, National University of Singapore, Singapore

Machining of hardened steel and other difficult-to-cut materials requires instant heat transfer from the cutting edge of the tool to improve tool life. Supply of high-volume and high-pressure coolant often provides the best answer. This paper deals with an experimental investigation on the effect of high-pressure coolant on workpiece hardness, comparing it with dry cut and conventional coolant. The effectiveness of high-pressure coolant is evaluated in terms of improvement of surface finish, reduction in tool wear and cutting forces, and control of chip shape. It is found that the cutting force is reduced, surface finish improved, and chip width is reduced with the use of high-pressure coolant.

Keywords: Chip shape; Cutting force; High-pressure coolant; Surface finish; Tool wear

1. Introduction

In the process of machining, a tool penetrates into the workpiece and removes the material in the form of chips. A major portion of the energy is consumed in the formation and removal of chips. The greater the energy consumption, the greater are the temperature and frictional forces at the tool–chip interface and consequently the higher is the tool wear.

Flood or conventional coolant is applied to remove the heat generated at the cutting zone. During machining [1,2], especially of very hard materials, much heat is generated by the friction of the cutter against the workpiece, which is one of the major causes of reduction in tool hardness and rapid tool wear. For this reason, conventional coolant is often used on the cutting tool, to prevent overheating. However, the main problem [3] with conventional coolant is that it does not reach the real cutting area. The extensive heat generated evaporates the coolant before it can reach the cutting area. The high cutting forces generated during machining will induce intensive pressure at the cutting edge between the tool tip and the workpiece. Conventional coolant might not be able to overcome this pressure and flow into the cutting zone to cool the cutting tool. Hence, heat generated during machining is not removed and is one of the main causes of the reduction in tool life.

With the use of high-pressure coolant during machining, the tool life and surface finish are found to improve significantly [4–7], which is said to be due to the decrease in heat and cutting forces generated. Therefore, there have been several studies on applying coolant at high pressure at the tool–chip interface, focused on a stationary single cutting edge in a turning operation. However, there is a need to improve machining conditions in intermittent milling, especially for case hardened materials.

The objective of this research is to evaluate the effectiveness of high-pressure coolant in improving the cutting parameters on work materials of different hardnesses during the end milling operation. The performance of high-pressure coolant is investigated by focusing on cutting forces, surface finish, tool wear, and chip shape, which are compared against dry cut and conventional coolant.

2. Experimental Set-up and Procedure

The experiment is carried out on a Makino V55 high-speed milling machine. A Sumitomo CDS3232R cutter equipped with a single uncoated A30N tungsten carbide insert and a TiAlCN coated insert has been used. A pressure coolant pump is used to provide a pressure of up to 20 bar. A through spindle coolant flow is used so that high-pressure coolant is able to penetrate through to the cutting zone. Six different hardnesses of ASSAB718 steel material are end milled during the experiment. It has been reported [8] that the machining characteristics are found to be effective using high pressure coolant at 17 bar with a feedrate of 0.05 mm $tooth^{-1}$, depth of cut of 0.35 mm and cutting speed of 150 m min^{-1}. Hence, further experiments were conducted with the observed cutting conditions and varying the hardness of the workpiece. The process parameters for this experiment are given in Table 1. For each workpiece hardness, samples with dry cut, conventional coolant and high-pressure coolant are analysed. The three iterations were

Correspondence and offprint requests to: Dr A. Senthil Kumar, Department of Mechanical Engineering, The National University of Singapore, 10 Kent Ridge Crescent, 119260 Singapore. E-mail: mpeask@nus.edu.sg

Table 1. Process parameters for the experiment.

Machining operation	End milling
Work material	ASSAB 718 supreme pre-hardened and tempered plastic mould steel
Range of hardness	25, 30, 35, 40 HRC
Cutting speed	150 m min^{-1}
Feedrate	0.05 mm tooth^{-1} = 74.6 m min^{-1}
Depth of cut	0.35 mm
Length of cut	206 mm
Diameter of cutter	32 mm
Number of insert	1
Type of inserts	Uncoated tungsten carbide and TiAlCN coated
Type of cooling	Dry cut (DC), conventional coolant (CC) and high pressure coolant (HP) at 17 bar

repeated for each hardness under the three cooling conditions to ensure consistency of results. The chips produced for each experiment are analysed with a scanning electron microscope (SEM). The surface finish of the machined workpiece was measured using a Mitutoyo surface tester. A Kistler piezo-electric dynamometer was used to measure the three components of cutting forces and a Sony tape recorder was used to record the data for analysis. Flank wear was also measured using a toolmaker's microscope. A diagram of the experimental set-up is shown in Fig. 1.

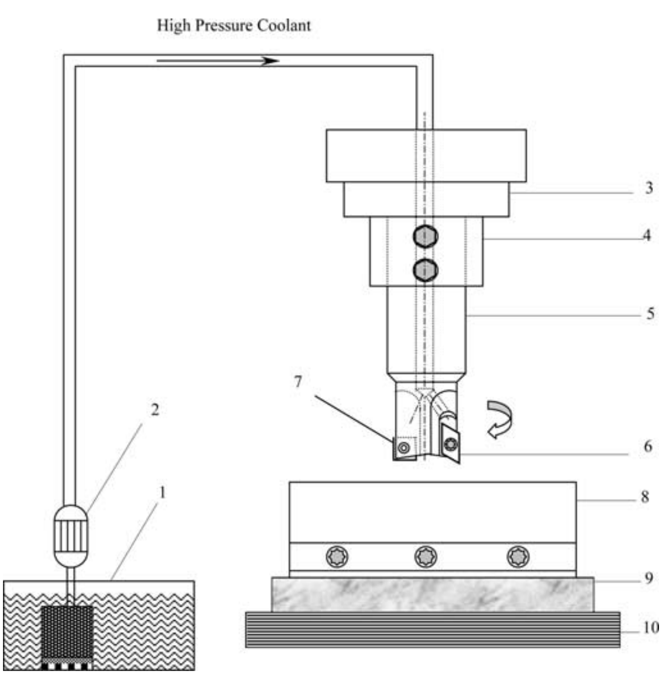

Fig. 1. Diagram of the experimental set-up. 1. Coolant tank; 2. High-pressure pump; 3. Spindle; 4. Tool holder; 5. Cutter; 6. Cutting insert; 7. Balancing insert; 8. Workpiece; 9. Dynamometer; 10. Machine table.

3. Results and Discussions

3.1 Effect of Cutting Forces

3.1.1 Uncoated Inserts

Owing to the brittleness of carbide tools, the experiment with uncoated inserts is carried out up to a hardness of 40 HRC. The three components of cutting forces are measured as shown in Fig. 2.

Under dry cut, all cutting force components increase with hardness. In fact, sparks are observed during machining of steel with hardness 35 HRC and above. However, the use of

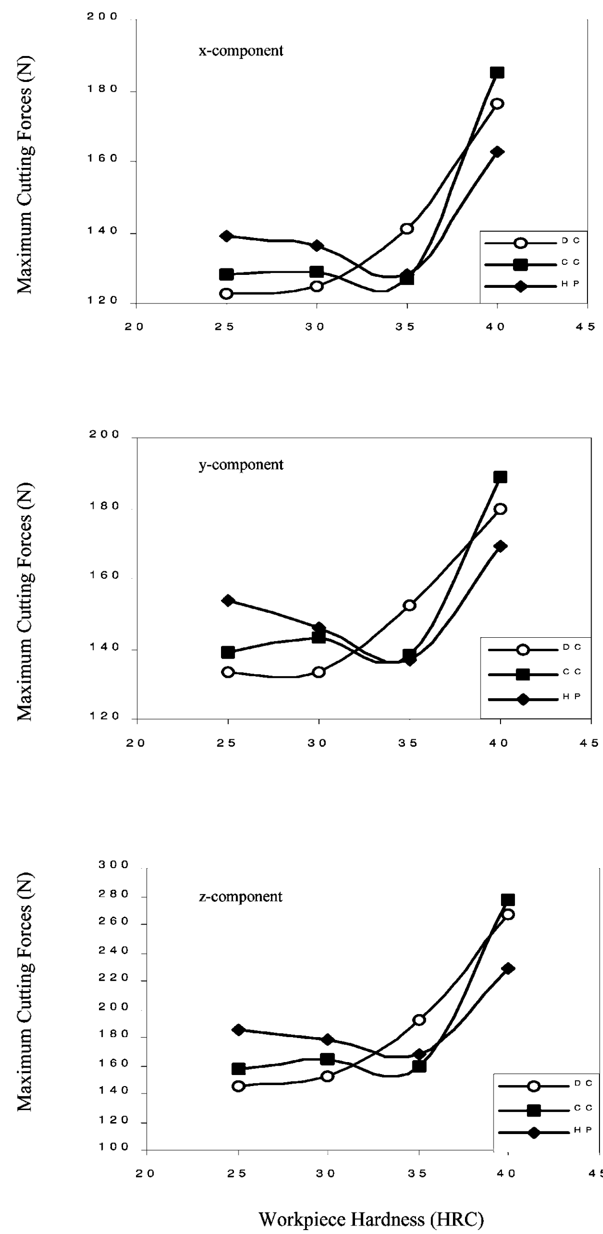

Fig. 2. Graph of maximum cutting forces vs. workpiece hardness for an uncoated insert after 3.19 min of cutting time. DC, dry cut; CC, conventional coolant; HP, high-pressure coolant.

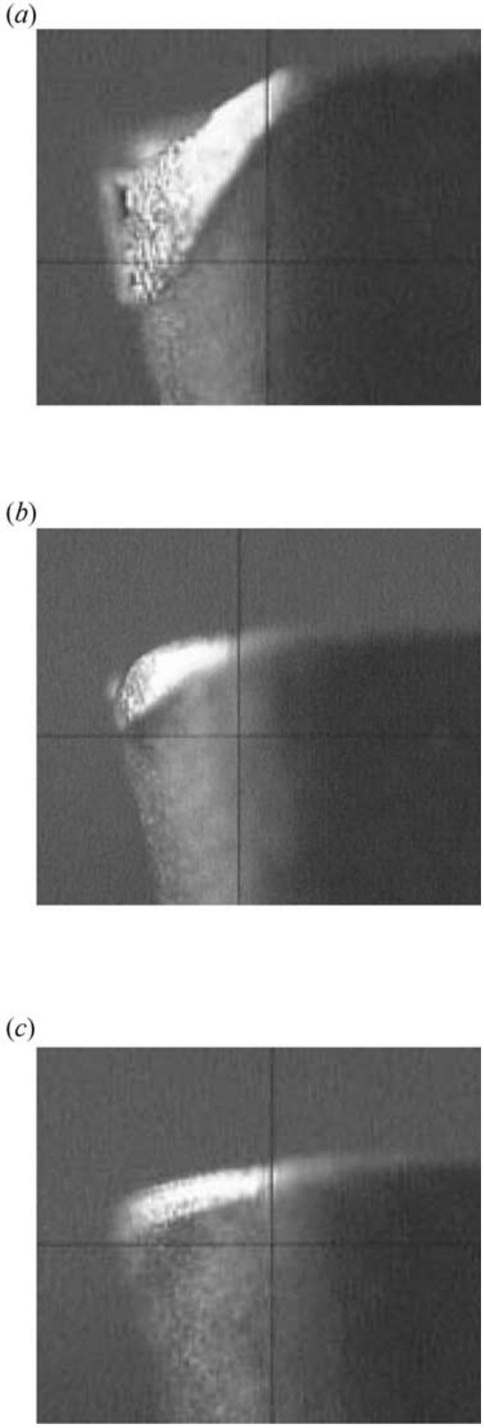

Fig. 3. (*a*) Dry cut. (*b*) Conventional coolant. (*c*) High-pressure coolant. Images of flank wear and tool failure at tool life of (*a*) and (*b*) = 3.19 min at 40 HRC under high pressure for uncoated insert.

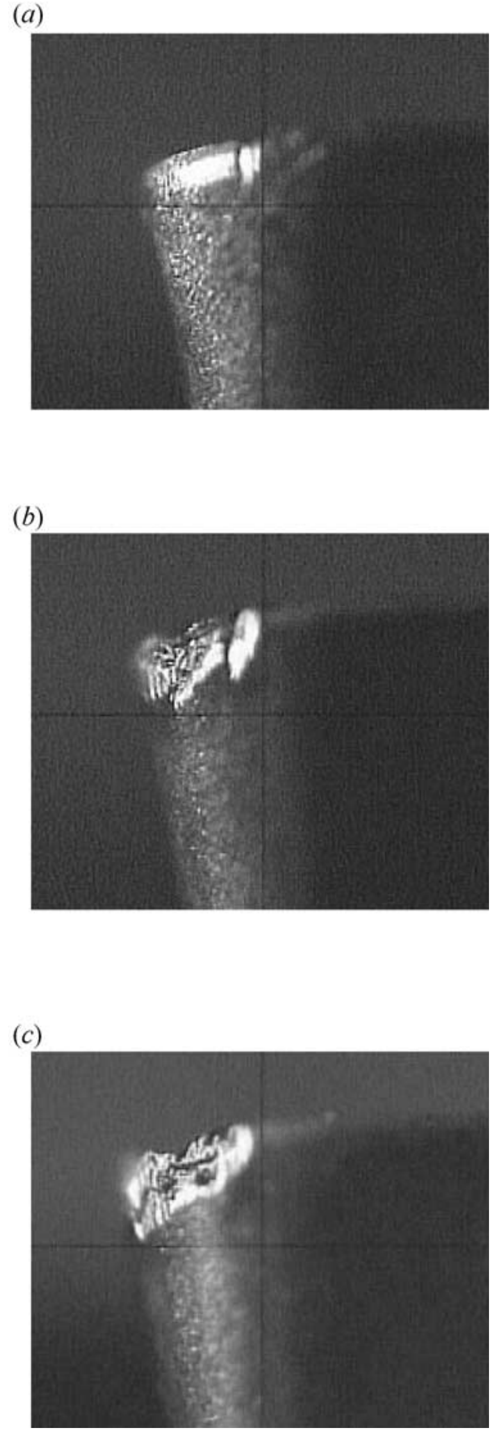

Fig. 4. (*a*) Dry cut. (*b*) Conventional coolant. (*c*) High-pressure coolant. Images of flank wear and tool failure at tool life of (*b*) and (*c*) = 12.26 min at 25 HRC under high pressure for uncoated insert.

high-pressure coolant lowers the tool–chip interfacial temperature and hence lowers the cutting forces between 35–40 HRC as compared to dry cut and conventional coolant. The sudden rise in the three force components between 35 and 40 HRC may be due to the increase in hardness of the workpiece above which the uncoated carbide insert is unable to cut. Above this hardness, rapid tool wear occurs, as can be seen in Fig. 3.

The influence of high-pressure coolant is more significant at higher workpiece hardness (35 HRC and above). As can be seen in Fig. 3, the tool wear with high pressure coolant is significantly better than that with dry cut and conventional coolant. However, dry cut gives the desired cutter performance at lower hardness, as can been seen in Fig. 4.

3.1.2 Coated Inserts

Comparing Figs 2 and 5, there is no significant difference in values of cutting forces between the coated and uncoated inserts. This is because the 5 μm thickness of coating used may not be the optimal thickness for the selected condition, as it has been established that film thickness plays an important role in the tool performance [9].

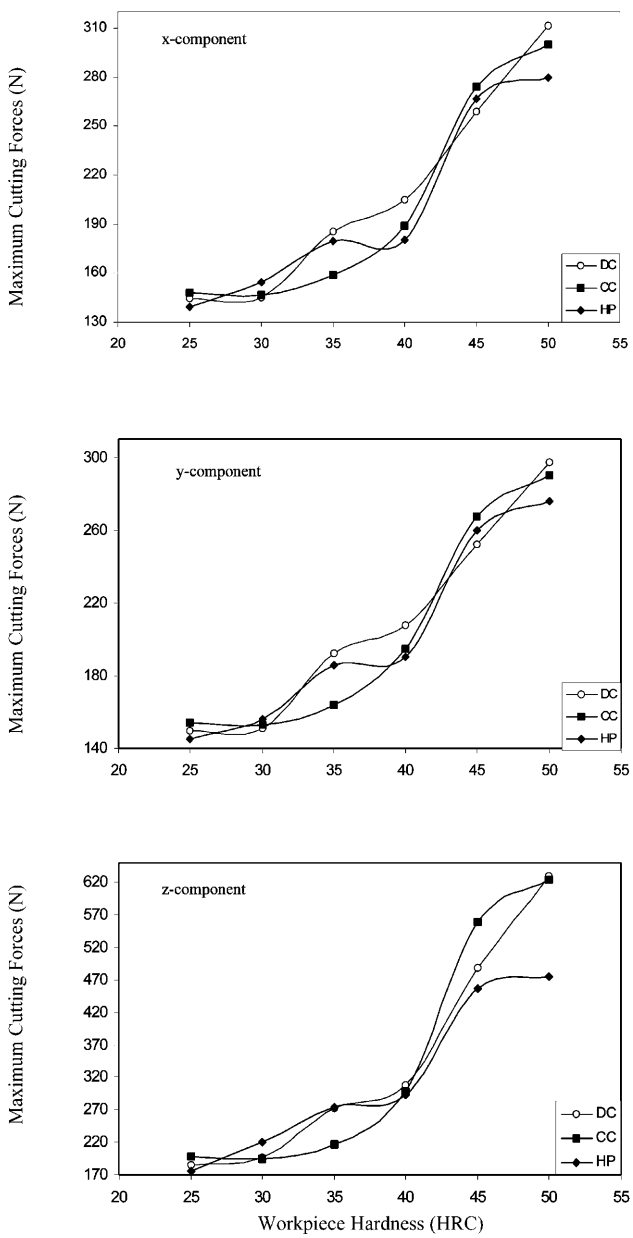

Fig. 5. Graph of maximum cutting force vs. workpiece hardness for a coated insert after 3.19 min of cutting time. DC, dry cut; CC, conventional coolant; HP, high-pressure coolant.

At 40 HRC, all cutting forces are the lowest with high-pressure coolant. The heat generated is so intense that the conventional coolant is unable to penetrate into the cutting zone. Although cooling occurs by film boiling at the depth of cut area, the heat comes from other places and increases the temperature, causing severe thermal shock, and hence microchipping occurs and the cutting force increases. In the case of high-pressure coolant, first, film boiling starts and persists for a short time, then vigorous nucleate boiling starts and forced convection takes place. The pressure is high enough to remove the heat from the cutting zone and cyclic thermal shock does not take place, hence, a lower cutting force is observed.

3.2 Effect of Surface Roughness

3.2.1 Uncoated Inserts

For all workpiece hardnesses, both conventional and high-pressure coolant always provide a much better surface finish than dry cut (see Fig. 6). The values of average surface roughness are well below 1.0 μm.

There is no pronounced difference on the influence of high-pressure coolant and conventional coolant at low hardness, 25–30 HRC. This may be due to the higher cutting forces obtained than in dry cut (see Fig. 2). However, at higher hardness, high-pressure coolant is able to improve surface roughness significantly. The coolant is able to reduce the contact area between the chip and rake face, resulting in a reduction of frictional forces at the tool–chip interface, as shown by the lower cutting forces (see Fig. 2). Therefore, the optimal hardness at which high-pressure coolant is a most effective lubricant in improving surface finish is above 35 HRC.

3.2.2 Coated Inserts

The quality of surface finish improves with coated tools, compared with uncoated tools. This is because the coating supplies lubrication that is absent in uncoated tools. From Fig. 7, it is clear that the average surface finish for high-pressure coolant is better than the dry cut and conventional coolant at 35–40 HRC. This indicates that the use of high-pressure coolant during machining has provided a better lubricating effect. Hence, this reduces the friction at the tool–workpiece interface and increases the surface finish. This agrees with the optimal hardness established by the uncoated insert.

3.3 Effect of Tool Wear

3.3.1 Uncoated Inserts

For lower hardness, 25–30 HRC, dry cut gives the best results in terms of tool wear, but high-pressure coolant results in the lowest flank wear at higher hardness, 35–40 HRC. In fact, flank wear decreases as the workpiece hardness increases with the application of high-pressure coolant. The three graphs

Fig. 6. Average surface roughness vs. workpiece hardness for an uncoated insert after 3.19 min of cutting time.

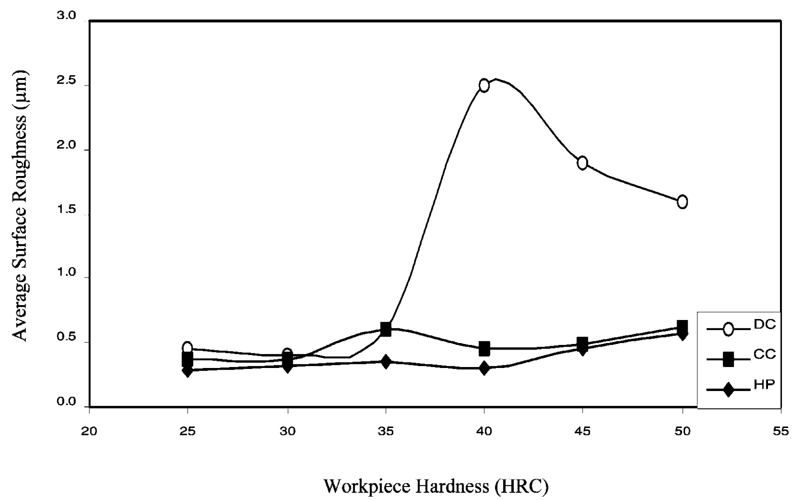

Fig. 7. Average surface roughness vs. workpiece hardness for a coated insert after 3.19 min of cutting time.

intersect at about 33 HRC. This is a transition point because, from this point, the effective zone of high pressure and dry cut for reducing flank wear is clearly mapped out.

At lower hardness, the major failure modes are of gradual uniform flank wear, whereas the use of both conventional and high-pressure coolant is detrimental. This can be explained by their similar modes of failure. Macrochipping of the cutting edge occurred after a short cutting time, owing to the development of microchips and cracks at the tool tip. Microchipping is observed at the flank face after the first machining pass. These microchips and microcracks gradually occurred and propagated with cutting time, leading to the failure of the tool. They may be caused by the alternating expansion and contraction of the tool surface, which leads to intense thermal cycles.

For higher hardness, high-pressure coolant is able to suppress premature tool failure. Catastrophic failure occurs without the development of microchips at the cutting edge under dry cut and conventional coolant conditions, resulting in the complete fracture of the entire tool nose.

3.3.2 Coated Inserts

The coating and the WC substrate work together as a system. It is believed that [10] the coating supplies wear resistance, lubrication, and a thermal barrier, whereas the substrate provides mechanical strength and fracture resistance. This explains the slightly lower flank wear obtained for a coated tool than for the uncoated insert, especially at higher hardnesses.

By examining the worn tool (see Fig. 8), it is found that coatings are always worn through on the cutting edge, even at a very early wear stage. Once the coating wears, the exposed substrate is subjected to wear processes immediately. At lower hardness (25–30 HRC), the application of coolant promotes [11] a "ductile" mechanism of tool wear, and the cutting edge undergoes micro chipping. This phenomenon [12] changes the geometry of the cutting edge and makes the actual rake angle more negative, which eventually leads to macrochipping of the insert and causes tool failure.

For higher hardness, above 40 HRC, owing to abrasion and/or adhesion, the tool becomes more "brittle" and cata-

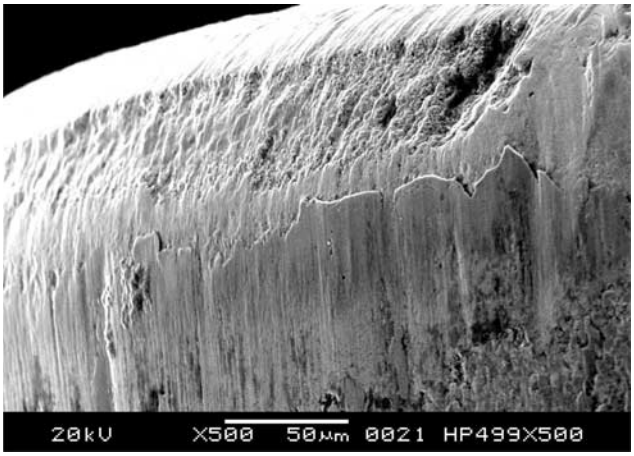

Fig. 8. A scanning electron microscope image of flank wear at 40 HRC with high-pressure coolant after 3.19 min of cutting time.

strophic failure results. High-pressure coolant is able to reduce the flank wear significantly; this is explained by the lower cutting forces and, hence, lower temperature observed during machining.

3.4 Effect of Chip Shape

3.4.1 Uncoated Inserts

Chips produced by dry cutting are of a long tubular type whereas for coolants, the chips are long and stringy (see Figs. 9, 10, and 11). Under dry cut, the chip is tightly curled and its radius of curvature is relatively smaller than that produced when using the coolant. This is because chips in dry cutting are subjected to intense heat, resulting in more plastic deformation than those obtained by coolant.

However, from the SEM Figs 12, 13, and 14, there is a distinct difference between the chips produced using conventional and high-pressure coolant. The serrated edge is found to be further apart and it is larger when using high-pressure coolant. This allows the heat to dissipate faster, thus lowering

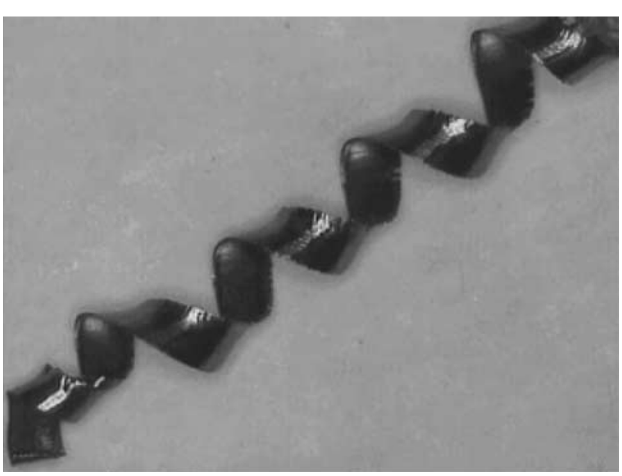

Fig. 9. The dry cut chip shape at 35 HRC for an uncoated insert.

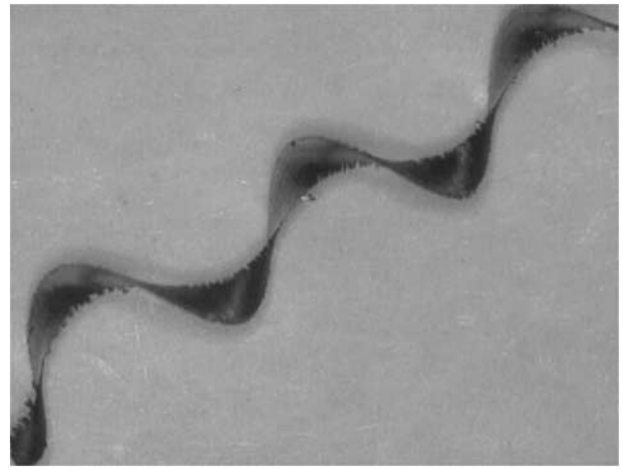

Fig. 10. The conventional coolant chip shape at 35 HRC for an uncoated insert.

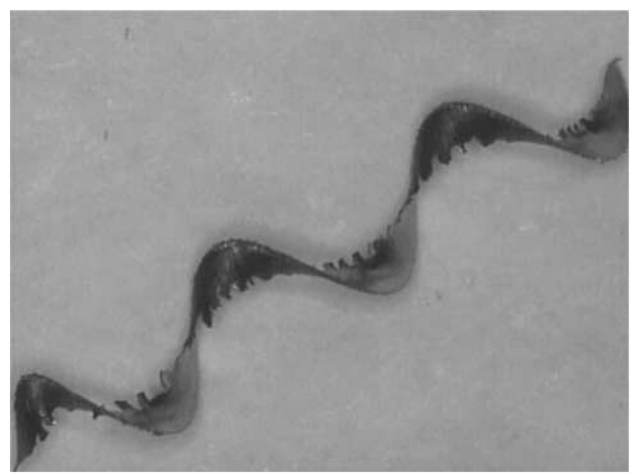

Fig. 11. The high-pressure chip shape at 35 HRC for an uncoated insert.

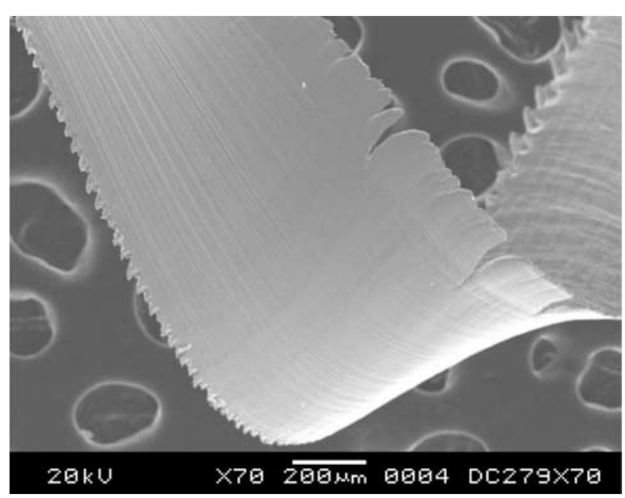

Fig. 12. A scanning electron micrograph showing a magnified dry cut chip at 35 HRC for an uncoated insert.

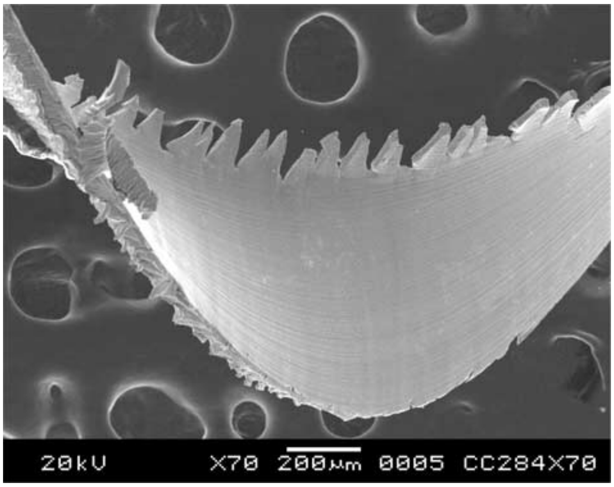

Fig. 13. A scanning electron micrograph showing a magnified conventional coolant chip at 35 HRC for an uncoated insert.

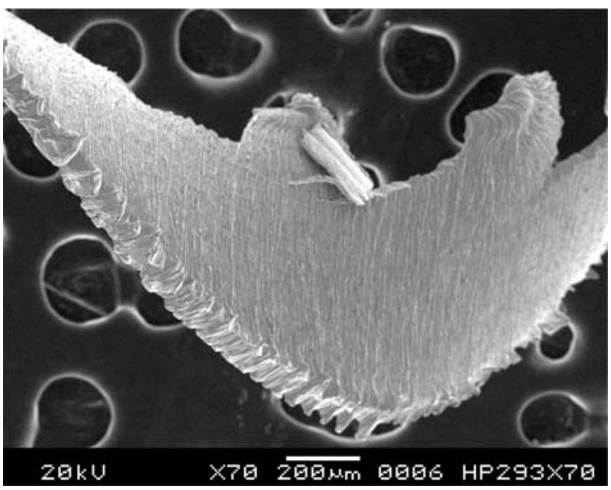

Fig. 14. A scanning electron micrograph showing a magnified conventional coolant chip at 35 HRC for an uncoated insert.

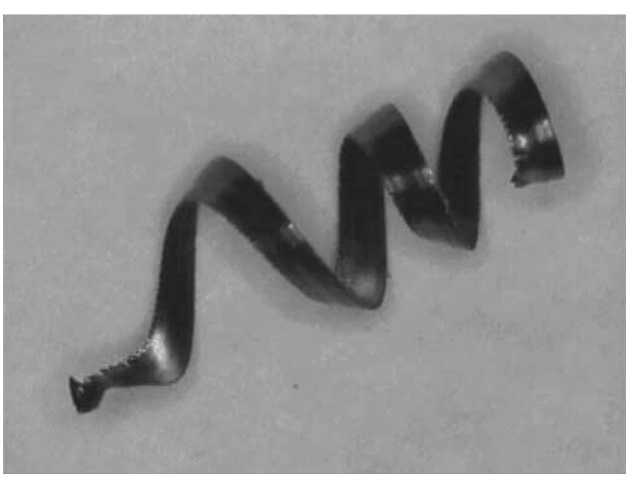

Fig. 15. The dry cut chip shape at 40 HRC for a coated insert.

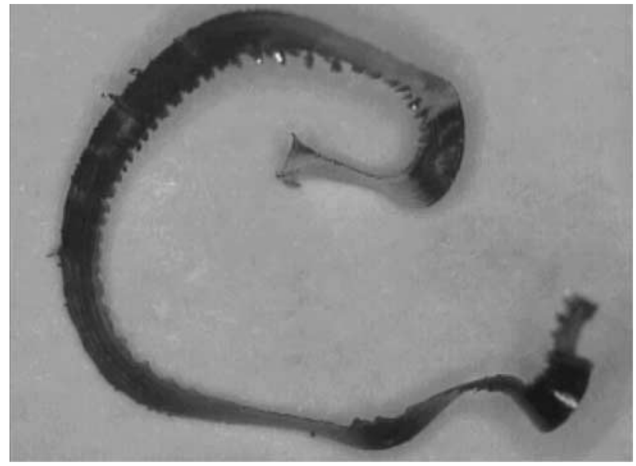

Fig. 16. The conventional coolant chip shape at 40 HRC for a coated insert.

Fig. 17. The high-pressure chip shape at 40 HRC for a coated insert.

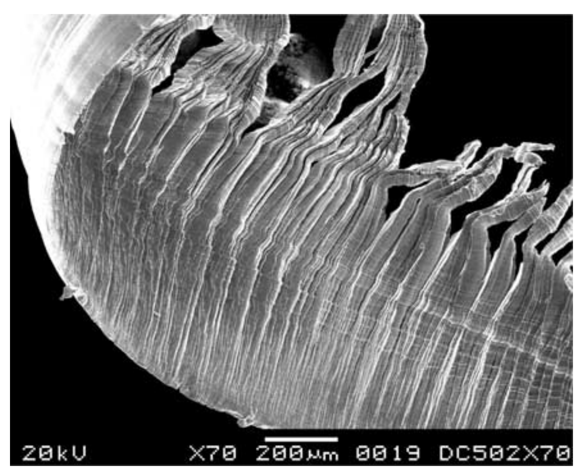

Fig. 18. A scanning electron micrograph showing chips under dry cutting at 40 HRC for a coated insert.

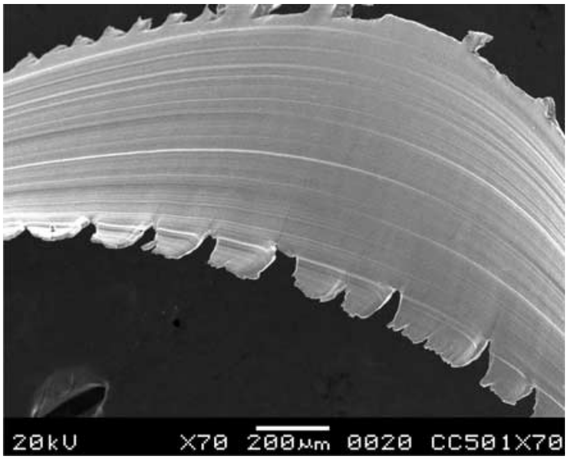

Fig. 19. A scanning electron micrograph showing chips under conventional coolant at 40 HRC for a coated insert.

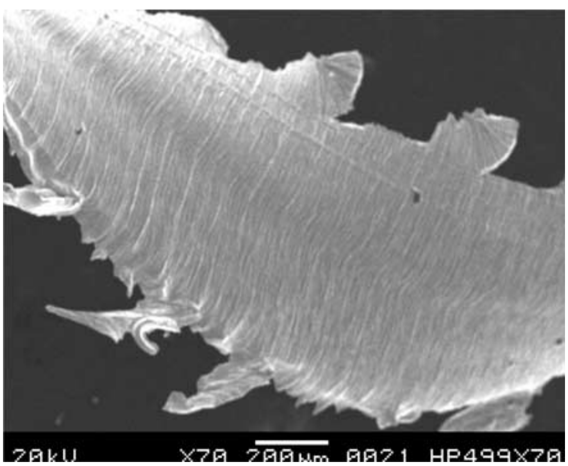

Fig. 20. A scanning electron micrograph showing chips under high pressure at 40 HRC for a coated insert.

the chances of heat being conducted into the cutting tool. This further explains the improved tool life and surface finish achieved at the optimal hardness.

3.4.2 Coated Inserts

From Figs 15, 16, and 17, it is clear that dry cutting produces short washer-type helical chips, which are relatively longer and are blue in colour, whereas chips produced by coolant are of the segmental type. This shows that coolant is able to penetrate into the tool–chip interface. The SEM Figs 18, 19, and 20 indicate that chips produced when using coolant are smoother. The serration of chips with the application of high-pressure coolant is wider and larger than those using conventional coolant. The hydraulic wedge created as the result of high-pressure coolant, forms a cushion at the tool–chip interface which reduces tool–chip contact length. This accelerates chip breakage and improves surface finish and tool life at 40 HRC.

4. Conclusions

The hardness of a workpiece plays an important role in the performance of tool. This is observed by the variation in cutting forces, surface roughness, flank wear and chip shape with workpiece hardness.

The application of high-pressure coolant produces a great reduction in flank wear and hence tool life and produces a significant improvement in surface finish for both uncoated and coated inserts, in a certain range of hardness. This is because the cutting temperature and forces are reduced when using high-pressure coolant.

The effective zone of high-pressure coolant in improving tool life and surface finish is found to be 35–40 HRC for the uncoated insert, whereas the optimal condition when using high-pressure coolant with a coated insert is 40 HRC.

For both coated and uncoated tools, the use of high-pressure coolant below the optimal hardness is found to be detrimental to the flank wear and hence tool life. This is due to the wear mechanism, and may be prompted by the ductility of the material, resulting in edge chipping that causes large tool wear and thus shortens tool life.

However, there is no significant difference in surface roughness with workpiece hardness for both types of insert, with the application of high-pressure coolant. Generally, the values of surface roughness are well below 1.0 µm, which is even better than for grinding or EDM. It can be concluded that high-pressure coolant is effective under the specified cutting conditions.

References

1. T. Othani and H. Yokogawa, "The effects of workpiece hardness on tool wear characteristics", Bulletin Japan Society of Precision Engineering, 22(3), September 1988.
2. Y. S. Yee, "A study on the parameters of high speed machining", B Eng thesis, National University of Singapore, 1998/99.
3. R. Wertheim and J. Rotberg, "Influence of high-pressure flushing through the rake face of the cutting tool", Annals CIRP, 41(1), pp. 101–106, 1992.
4. R. Kovacevic, C. Cherukuthota and R. Mohan "Improving the surface quality by high pressure waterjet cooling assistance", Geomechanics 93, pp. 305–310, Rakowski Balkema, Rotterdam, 1994.
5. R. Lindeke, F. Schoeing Jr, A. Khan and J. Haddad, "Cool your jets", Cutting Tool Engineering, pp. 31–37, October 1991.
6. M. Mazukiewicz, Z. Kubala and J. Chow, "Metal machining with high pressure water-jet cooling assistance", Journal of Engineering for Industry, 111, pp. 7–12.
7. R. R. Lindeke, F. C. Schoening Jr, A. K. Khan and J. Haddad, "Machining of titanium with ultra-high pressure through insert lubrication/cooling", Transactions of NAMRI/SME, pp. 154–161, 1991.
8. M. Rahman, A. Senthil Kumar and M. R. Choudhury, "Identification of effective zones for high pressure coolant in milling", Annals CIRP, 49(1), pp. 47–52, 2000.

9. Y. L. Su, S. H. Yao, C. S. Wei, C. T. Wu and W. H. Kao, "Design of a titanium nitride-coated WC milling cutter", Journal of Material Processing Technology, 86, pp. 233–236, 1999.
10. J. Gu, G. Barber, S. Tung and R.-J. Gu, "Tool life and wear mechanism of uncoated and coated milling inserts", Wear, 225–229, pp. 273–284, 1999.
11. G. Boothroyd and W. A. Knight, Fundamentals of Machining and Machine Tools, 2nd edn, Marcel Dekker, New York, 1995.
12. J. Gu, G. Barber, S. Tung and R.-J. Gu, "Tool life and wear mechanism of uncoated and coated milling inserts", Wear, 225, pp. 273–284, 1999.