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# HIGH PRESSURE WATERJET COOLING/LUBRICATION TO IMPROVE MACHINING EFFICIENCY IN MILLING

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**Abstract**—The efficiency of the metal cutting operations depends upon the thermal/frictional conditions at the tool-chip interface. The use of high pressure waterjet as a coolant/lubricant to improve the thermal/frictional conditions in milling operations was studied here. The influence of high pressure waterjet delivered into tool-chip interface in two different methods, namely, waterjet injected directly into the tool-chip interface through a hole in the tool rake face, and waterjet injected into tool-chip interface through an external nozzle, was explored in this study. The effectiveness of these developed methods was evaluated in terms of cutting force, surface finish, chip shape and tool wear.

## 1. INTRODUCTION

Machining is a process of material removal in which the loss of material is caused by effecting a relative motion between tool and workpiece. Due to removal of material in the form of chips, new surfaces are cleaved from the workpiece accompanied by a large consumption of energy. The mechanical energy necessary for the machining operation is transformed into heat, leading to conditions of high pressure, high temperatures and severe thermal/frictional conditions at the tool-chip interface. The greater the energy consumption, the more severe are the thermal/frictional conditions, consequently making the metal cutting process more and more inefficient in terms of tool life, dimensional accuracy and material removal rate. With the advent of carbide tools and other new methods of machining, the efficiency of the metal cutting operations has improved to a certain extent under normal cutting conditions. However, improving the performance of metal cutting operations in high speed machining and in the case of machining difficult-to-machine materials is still a major concern. It was found that the efficiency of metal cutting operations depends to a large extent on the effectiveness of the cooling/lubrication provided. A flood of fluid directed over the back of the chip is the most common method of applying the cutting fluid. However, this method loses its effectiveness at higher cutting speeds. It was found that a high pressure coolant/lubricant jet injected into the tool-chip interface provides effective cooling/lubrication and consequently improves the machining performance of the tool.

A number of attempts [1-6] were made in the past to improve cooling/lubrication in high speed machining and in the case of machining of difficult-to-machine materials by the use of a high pressurized coolant/lubricant jet. In general, all attempts to apply pressurized cutting fluid can be classified into three groups, namely, coolant/lubricant jet injected into tool-chip interface through an external nozzle [1, 5], jet delivered into the clearance between flank and machined surface [2], and jet injected directly through the tool rake face into tool-chip interface [3, 4, 6]. The results achieved by these investigators were very encouraging. Cutting forces were reduced, chip shape, surface quality and tool life improved, thereby increasing the metal removal rate, and improving the overall performance of the machining operation.

From all these investigations, it was evident that applying cutting fluid in the form

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of a jet at higher pressures into the cutting zone is more beneficial than conventional cooling techniques. A high pressure waterjet brought as a coolant/lubricant through a hole in the rake face of tool reduces secondary shear, lowers interface temperatures, and changes chip shape. Until now, investigations carried out in this direction were, in general, limited to low pressures where the cutting fluid is not capable of penetrating deep enough into the tool–chip interface to dissipate heat as quickly as possible from the appropriate regions in the cutting zone. Further, all these investigations were limited to stationary single edge cutting tool operations. However, there is a great need to improve machining performance by improving cooling methods in the case of rotary tool operations like drilling and milling especially while machining difficult-to-machine materials.

The objective of this study is to evaluate the effectiveness of high pressure waterjet cooling/lubrication of tool–chip interface accomplished in two different methods. In the first method, waterjet at a high pressure was directed into the tool–chip interface through a hole drilled in the tool rake face. This developed cooling/lubrication system was used in conjunction with face milling operation. In the second method, a waterjet at high pressures was injected into the tool–chip interface, through a remote nozzle. This method of cooling/lubrication was tested in the case of down milling operation while machining titanium alloy. The effectiveness of the above cooling methods was evaluated in terms of cutting force, surface finish, tool life and chip shape.

## 2. EXPERIMENTAL SETUP AND PROCEDURE

### 2.1. *High pressure waterjet cooling through tool rake face*

The experimental setup shown in Fig. 1, where a high pressure waterjet was injected through the tool rake face, consists of a high pressure intensifier pump, vertical milling machine, four component dynamometer, charge amplifier, A/D convertor, PC/AT with suitable software, printer and stainless steel workpiece. In order to conduct this study, a high pressure coolant/lubrication system which is suitable for rotary cutting tools was developed [7–9]. High pressure water from the intensifier pump is brought to the milling machine through a stainless steel tubing. The compressed water from

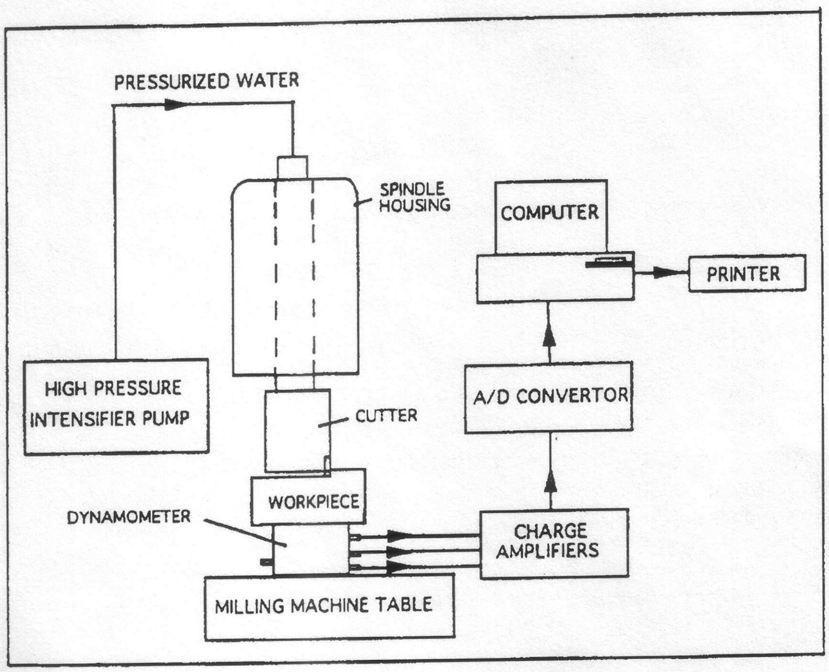



Fig. 1. Experimental setup—waterjet through tool rake face.

the stationary high pressure tubing is supplied to the rotary cutter through a swivel, hollow draw bar, and sapphire orifice located at the end of the channel which connects to the EDM drilled hole in the carbide insert. The design of high pressure waterjet coolant/lubricant system through tool rake face is shown in Fig. 2.

The orientation of the jet towards the tool–chip interface depends upon the location of the hole in the insert. A hole located close to tip of tool would deliver the waterjet effectively into hot zones of tool–chip interface. However, the hole located too close to tool tip reduces the strength of tool tip, consequently leading to its chip off. Since it is not economically feasible to locate the hole by mere trial and error, an on-line optical sensing technique was developed. The results from these tests suggested that a hole positioned at a distance of 1.25 mm from tool tip along the center line is the best location for the cutting conditions employed in this study. Photographs of chip flow corresponding to an insert with hole positioned at a distance of 1.25 mm from tool tip, and the orientation of waterjet towards tool–chip interface are shown in Fig. 3.

The workpiece is clamped on the top of a four component dynamometer. Cutting force exerted by the tool is measured along the three components, $X$, $Y$ and $Z$. The cutting parameters were chosen at four different levels, and the stainless steel samples were cut for a length of about 75 mm by varying each parameter and keeping the other parameters constant at their mean values. The process parameters employed are given in Table 1. The chips produced under various cutting conditions were collected for analysis, and the surface finish of the cut profile was measured in terms of roughness average, $R_a$. In order to understand the influence of hydraulic parameters on machining performance, the above experiment is repeated for different water pressures and orifice diameters.

## 2.2. *High pressure waterjet through external nozzle*

The experimental setup in the case of second method shown in Fig. 4 (waterjet delivered at high pressures through a remote nozzle into tool–chip interface) consists of a high pressure intensifier pump, horizontal milling machine, three component

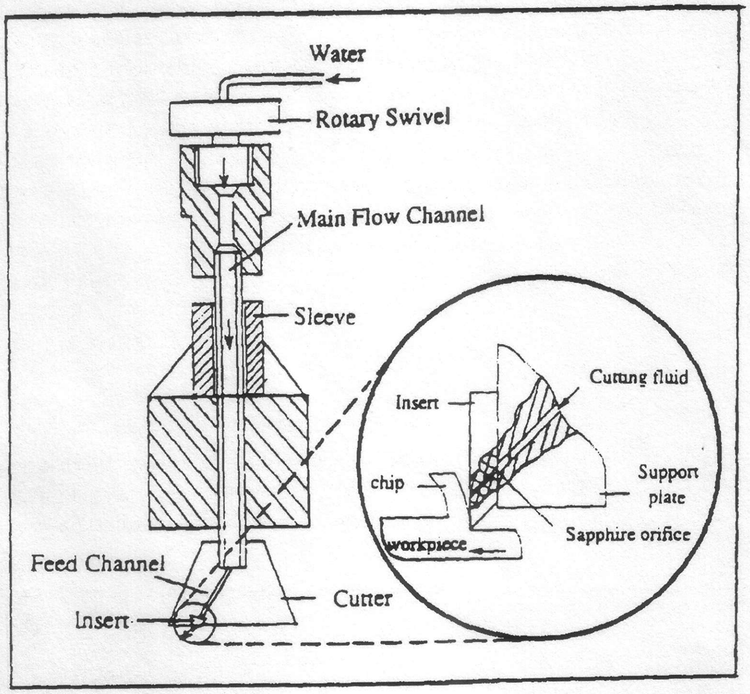
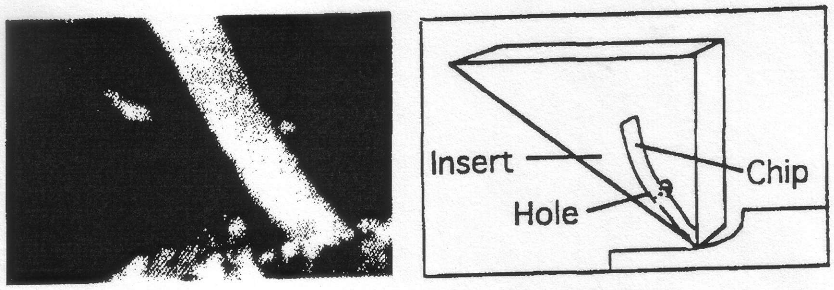
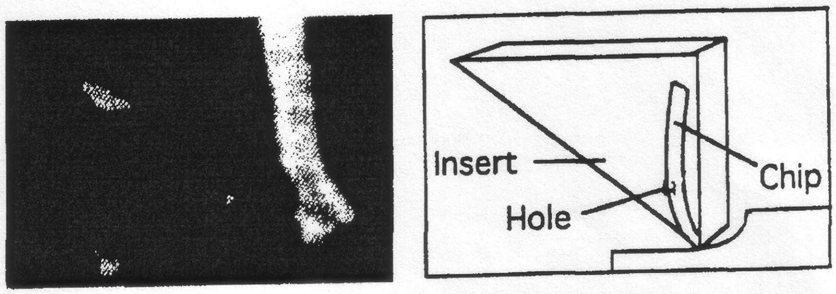


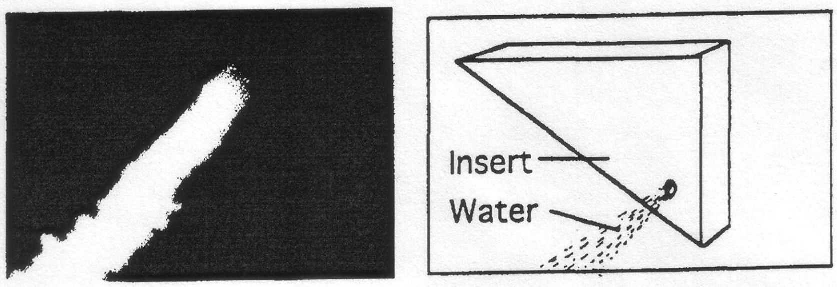

Fig. 2. High pressure waterjet coolant/lubricant system through tool rake face.




(a) Speed = 71.8 m/min, feed = 12.7 mm/min
depth =0.89 mm




(b) Speed = 91.7 m/min, feed = 8.9 mm/min
depth =1.02 mm




(c) Pressure = 68.8 MPa,
orifice dia. = 0.125 mm

Fig. 3. Photographs showing the position of hole relative to chip (a) and flow of waterjet through rake face (b).

dynamometer, data acquisition system, portable surface tester and a tool maker's microscope. This developed coolant/lubricant system [10] was used in conjunction with a down milling operation on a horizontal milling machine. Waterjet brought from the high pressure intensifier pump was directed through an external nozzle at a low rake angle from a direction perpendicular to the cutting edge in such a way that it hits the rake face of the cutting insert approximately 2 mm before reaching the cutting edge.

The workpiece is clamped on the top of a three-component dynamometer. Different levels of cutting speeds, and depths of cut were employed keeping the feed rate fixed. The process parameters employed in these experiments are shown in Table 2. Tool life tests were carried out by repeated visual examination of flank wear at several stages during machining. Further, in order to study the influence of water pressure, separate tests were conducted. A new cutting edge was used for every test performed. The chip shape produced was analyzed, and the surface finish of cut was measured in terms of roughness average, $R_a$.

Table 1. Process parameters—waterjet through tool rake face

| | |
|---|---|
| | Constant conditions |
| Workpiece material | Stainless steel AISI 304 |
| Diameter of the cutter | 50.8 mm |
| Type of operation | Face milling |
| Max number of inserts | 5 |
| Number of inserts used | 1 |
| Type of the insert used | TPG322 (K313) |
| Geometry of the insert | Rake angle = 0<br>Nose radius = 0.8 mm<br>Clearance angle = 11 |
| | Experimental variables—phase 1 |
| Range of cutting speed | 47.9–95.8 m/min |
| Range of cutting feed | 5.10–12.70 mm/min |
| Range of depth of cut | 0.51–1.27 mm |
| Length of the cut | 75 mm |
| Type of cooling used | High pressure waterjet |
| Water pressure | 68.8 MPa |
| Orifice diameter | 0.250 mm |
| | Experimental variables—phase 2 |
| Cutting speed | 71.8 m/min |
| Cutting feed | 8.9 mm/min |
| Depth of cut | 0.89 mm |
| Length of the cut | 75 mm |
| Type of cooling used | Flood and high pressure waterjet |
| Range of water pressure | 0–110 MPa |
| Range of orifice diameter | 0–0.45 mm |

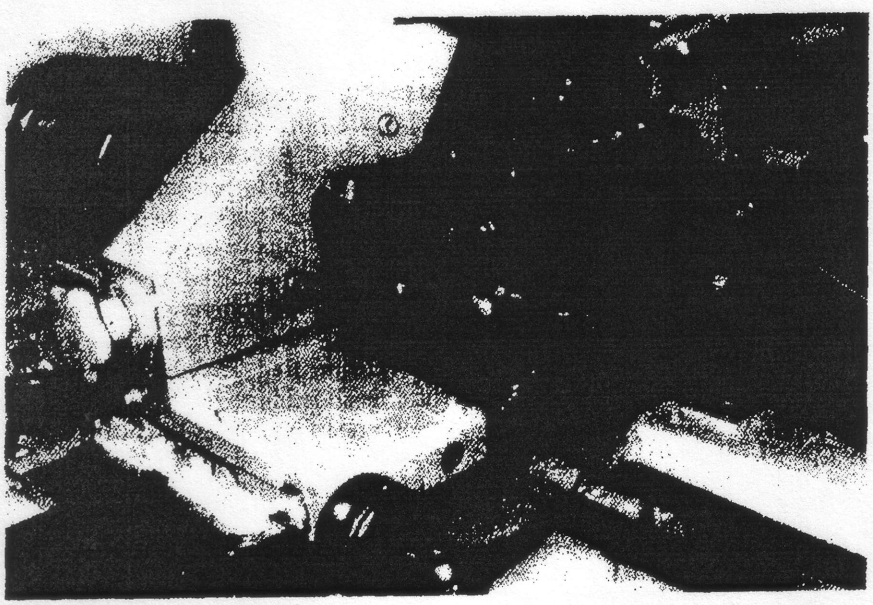


Fig. 4. Experimental setup—waterjet through external nozzle.

Table 2. Process parameters—waterjet through external nozzle

| Constant conditions | |
|---|---|
| Workpiece material | Titanium Ti-6AI-4V |
| Type of operation | Down milling |
| Number of inserts used | 1 |
| Type of the insert used | SPG633 (K8735) |
| Experimental variables | |
| Range of cutting speed | 70–180 m/min |
| Feed/tooth | 0.27 mm |
| Range of depth of cut | 0.76–1.52 mm |
| Type of cooling used | High pressure waterjet |
| Orifice diameter | 0.51 mm |
| Range of water pressure | 0–193 MPa |

## 3. RESULTS AND DISCUSSION

### 3.1. *High pressure waterjet cooling through tool rake face*

In order to investigate the influence of high pressure waterjet (applied at a constant pressure of 68 MPa and through an orifice of dia. 0.125 mm) in terms of cutting force, surface finish, tool wear and chip shape, the first phase of experiments was carried out. The experiments were conducted over a range of cutting speeds (47–96 m/min), feeds (5–13 mm/min) and depth of cut (0.5–1.3 mm). In order to study the effect of varying pressures (0–110 MPa) and orifice diameters (0–0.45 mm) on the performance of high pressure waterjet cooling, another set of experiments were performed. The conventional cutting parameters were kept constant during this study (speed, 79.8 m/min; feed, 8.9 mm/min; depth of cut, 0.89 mm). The evaluation of the effectiveness of high pressure cooling is based upon the comparison of cutting forces, surface quality, chip shape and tool wear obtained under high pressure waterjet cooling with those obtained in the case of flood cooling.

A typical overlay of cutting force components under flood cooling and high pressure waterjet cooling obtained under various cutting speeds, feeds and depths of cut are shown in Fig. 5. The variation in the $X$ component of force with increase in cutting speed is shown in Fig. 5(a). It was observed that the cutting force components obtained with the aid of high pressure waterjet cooling are always less than those obtained in the case of flood cooling. A drastic reduction of about 40% was observed in the cutting force components. Figure 5(b) shows a typical overlay of force component with varying feed. As expected, increase in feed rate tends to increase the cutting force components. Here also, it was found that the cutting force components obtained in the case of high pressure waterjet cooling are always less than those obtained in the case of flood cooling. The influence of depth of cut on cutting force component for two different types of cooling is shown in Fig. 5(c). The cutting force component is much less in the case of high pressure waterjet cooling as compared to flood cooling. With the application of high pressure waterjet, surface finish is improved significantly as shown in Fig. 6 where roughness average is plotted against variation in cutting speed, feed and depth of cut.

A plot of cutting force components with change in water pressure is shown in Fig. 7(a). The $X$ component force was found to decrease drastically with increase in water pressure. The trend observed in the case of $Y$ component and $Z$ component force is similar. Figure 7(b) shows the variation in force components with variation in orifice diameter. From Fig. 8, it can be clearly seen that with increase in water pressure and orifice diameter, the surface finish gradually improves with the improvement more significant at lower pressures than at higher pressures and orifice diameters. Figure 9 shows typical chip shape obtained in the case of flood cooling and high pressure waterjet cooling under similar cutting conditions. It can be seen from this figure that

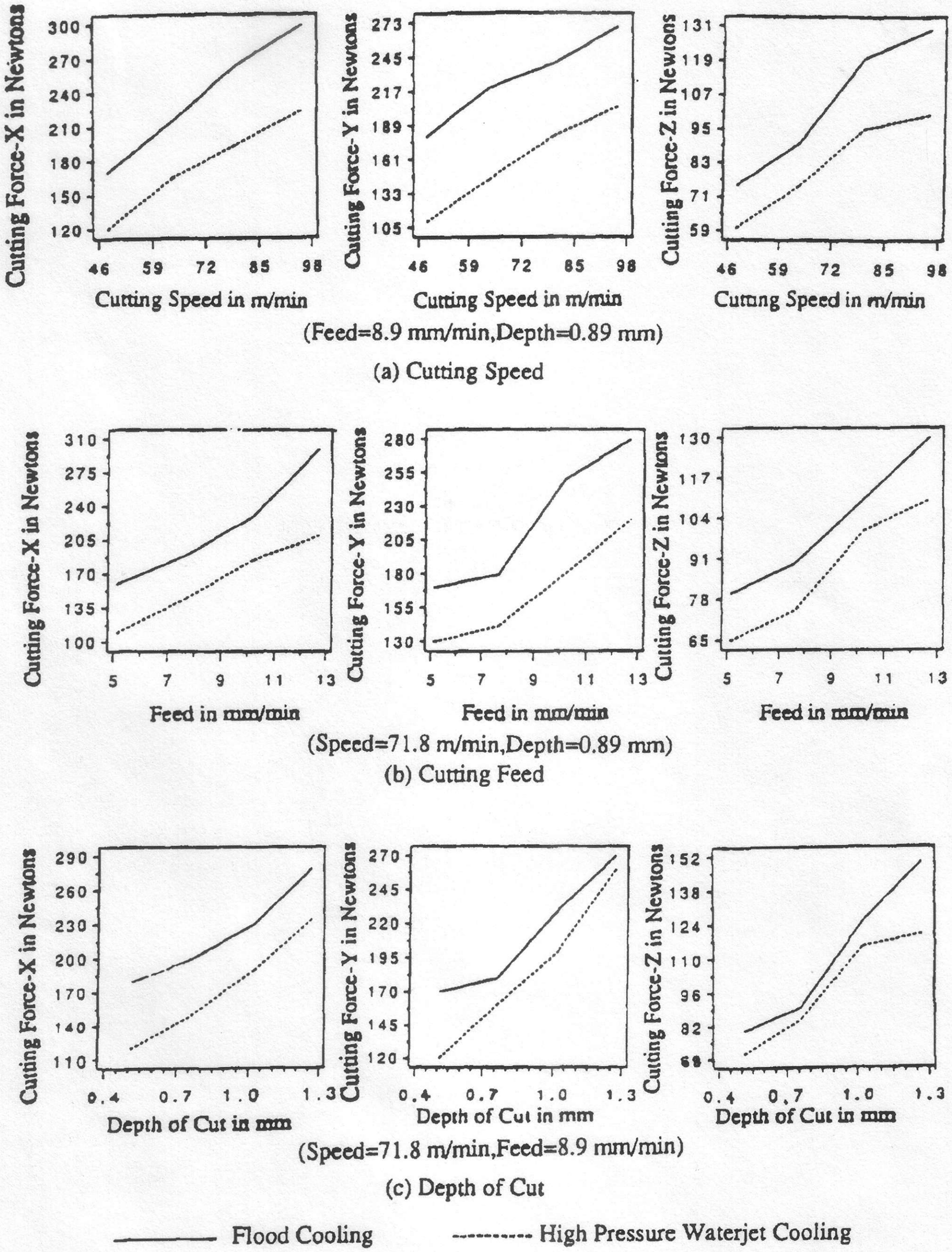



Fig. 5. Typical plot of cutting force component vs (a) cutting speed, (b) feed and (c) depth of cut.

the chips obtained in the case of high pressure waterjet cooling are much smaller than those obtained under similar cutting conditions in the case of flood cooling. Further, the chips obtained in the case of flood cooling were found to be blackened due to intense heat generated at tool–chip interface. The scanning electron microscope photographs of chips obtained under different water pressures and orifice diameters are shown in Fig. 10. The tool–chip contact surface obtained in the case of flood cooling is very rough indicating the intense shearing action in the case of flood cooling. However, the tool–chip contact surface obtained with the help of high pressure waterjet cooling is smooth indicating the absence of high shearing forces. Photographs of carbide inserts used for high pressure waterjet cooling and flood cooling clearly indicate the

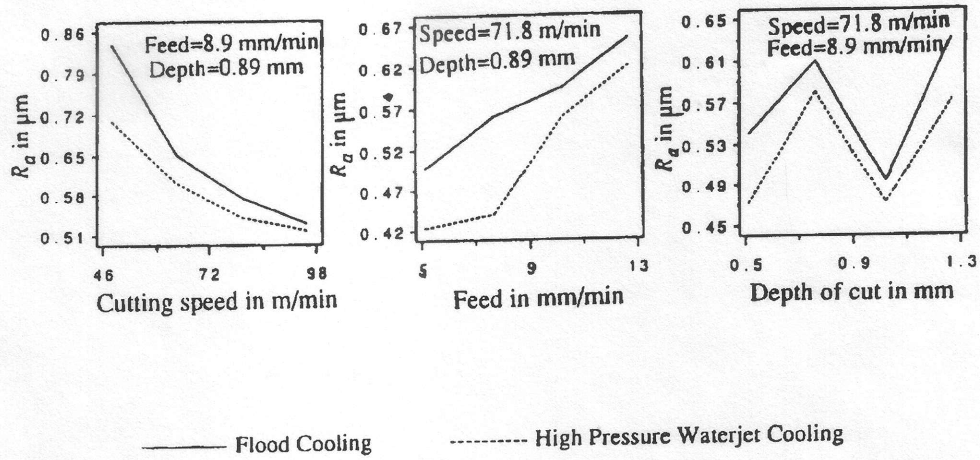
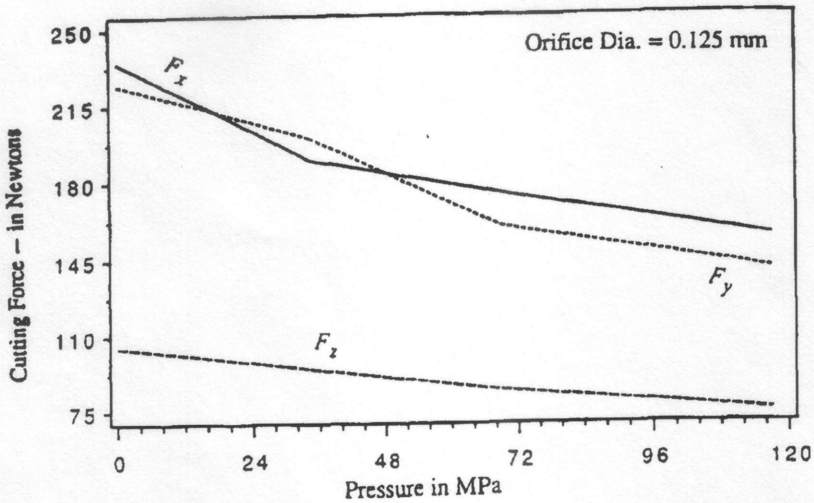



Fig. 6. Surface roughness ($R_a$) vs cutting parameters.

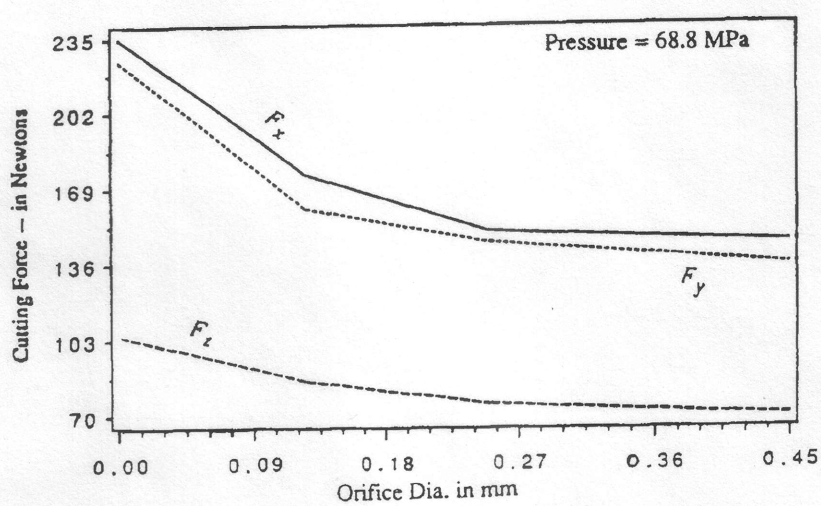
influence of high pressure waterjet on flank wear. The photograph of insert after 50 min of operation in conjunction with high pressure waterjet cooling is shown in Fig. 11(a) and the corresponding insert used in the case of flood cooling is shown in Fig. 11(b). It can be observed that the width of flank wear is much higher in the case of flood cooling as compared to that in the case of high pressure waterjet cooling indicating a longer tool life in the case of high pressure waterjet cooling.

The reduction in cutting forces, tool wear, and improvement in efficiency of metal cutting operation with the aid of high pressure waterjet cooling/lubrication could be due to several reasons. The penetration of the waterjet into tool–chip interface results in the formation of a hydro-wedge which provides hydrodynamic lubrication by serving as a boundary lubricant preventing to a large extent the intimate contact between tool and chip. In the case of flood cooling, the intimate metallic contact between chip and tool results in an extreme secondary deformation zone, encouraging tool wear. The greater the area of contact, the higher is the friction at the tool–chip interface. In the case of high pressure waterjet cooling, the formation of hydro-wedge at tool–chip interface tends to keep the chip away from the tool rake face and thereby promoting self-breakage effect. The presence of much bigger serrations on the contact surface in the case of flood cooling as compared to high pressure waterjet cooling is an indication of intense shearing action in the case of flood cooling. The improvement in the effectiveness of the cooling/lubrication at higher pressures and orifice diameters can be related to formation and growth of hydro-wedge. An increase in water pressure and orifice diameter is accompanied by a corresponding growth in hydro-wedge which tends to keep the chip farther and farther away from tool–chip contact surface.

The effectiveness of cooling/lubrication action of high pressure waterjet was found to increase with increase in water pressure and orifice diameter. But after reaching certain optimum value of water pressure and orifice diameter, a further increase in hydraulic parameters was not found to be very beneficial in reducing cutting forces and improving surface finish, chip shape and tool life. The chip flow in the case of face milling is highly fluctuating and unpredictable making it difficult to locate the hole in such a way that the jet orientation is appropriate for all cutting conditions. However, the delivery of jet into the tool–chip interface could be improved by directing the jet in the form of a spray through minute holes made in the tool insert or by providing grooves on the insert which act as guideways in directing the jet into the tool–chip interface. Further investigations need to be carried out in this direction.




(a) Water Pressure



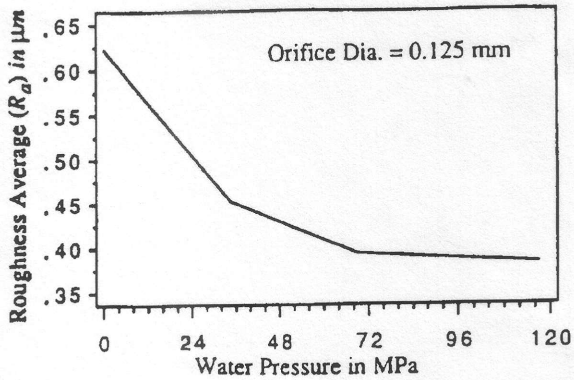

(b) Orifice Diameter

(Speed=71.8 m/min, Feed=8.9 mm/min, Depth=0.89 mm)

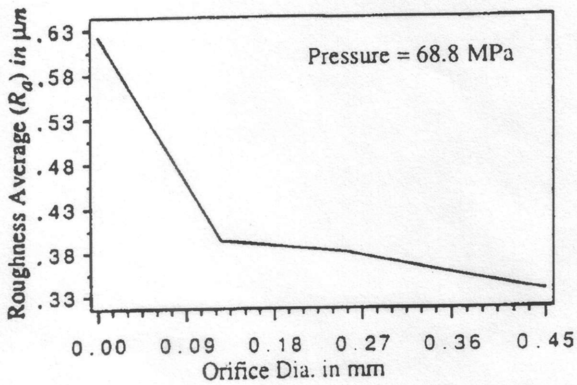
Fig. 7. Components of cutting force vs (a) water pressure and (b) orifice diameter.

### 3.2. *High pressure waterjet through external nozzle*

In order to investigate the influence of a high pressure waterjet injected at high pressures into tool–chip interface through an external nozzle, experiments were carried out by performing down milling of titanium alloy. The experiments were conducted over a range of cutting speeds (70–180 m/min), depth of cut (0.76–1.52 mm), and at a fixed feed of 0.27 mm/tooth under the influence of high pressure waterjet applied through an orifice of diameter 0.51 mm. The results obtained from these experiments were compared with those obtained under similar cutting conditions using conventional cooling technique. Further, in order to study the influence of variation in waterjet pressure on machining performance, experiments were conducted over a range of water




(a) Water Pressure




(b) Orifice Diameter

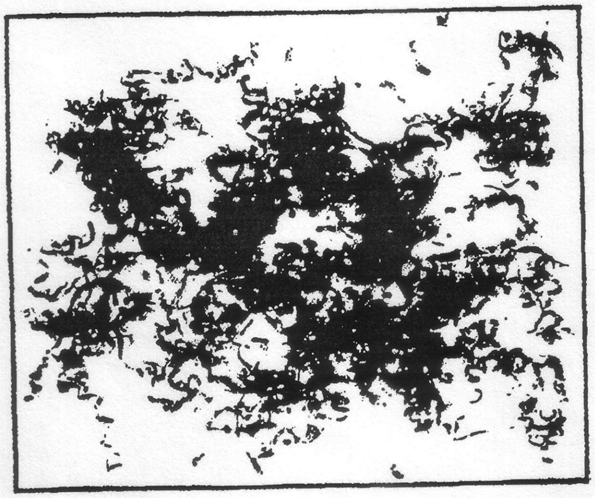
(Speed=71.8 m/min. Feed=8.9 mm/min. Depth=0.89 mm)

Fig. 8. Surface roughness ($R_a$) vs (a) water pressure and (b) orifice diameter.

pressures (69–200 MPa). The effectiveness of this method was evaluated in terms of surface finish, chip shape and tool life.

Figure 12 shows a plot of surface roughness average, $R_a$, vs cutting speed for conventional flood cooling and in the case of high pressure waterjet cooling under different pressures (69, 138, 200 MPa). In general, an increase in the cutting speed leads to a deterioration of surface finish. With the application of high pressure waterjet, the value of $R_a$ is drastically reduced indicating the improvement in surface quality. However, a further increase in water pressure was not found to improve the surface quality appreciably. This can be seen from the closely spaced curves in Fig. 12 corresponding to pressures of 69, 138 and 200 MPa, respectively. Figure 13 shows the plot of surface roughness average, $R_a$, plotted against waterjet pressure for different cutting speeds. It can be seen that with increase in waterjet pressures, the quality of the surface improves. However, this is not significant at higher pressures. Also, the influence of high pressure waterjet in improving machining conditions is more pronounced at higher cutting speeds than at lower speeds as can be seen from the curve corresponding to 183 m/min. The formation and removal of chips is not very crucial in the case of

(a) Flood cooling



(b) High pressure water cooling
(pressure = 68.8 MPa, orifice dia. = 0.125 mm)

Fig. 9. Typical chip shape for (a) flood cooling and (b) high pressure waterjet cooling.

intermittent cutting operations like milling. However, in order to provide a better understanding of material removal, chips were collected after every test and analyzed. In the case of conventional cooling, it was found that the chips had a yellowish burnt color. Further, some of the chips produced in conventional cooling were welded to the cutting edge of the tool which was avoided in the case of high pressure waterjet cooling. However, an additional increase in water pressure does not prove to be too advantageous in improving the formation and removal of chips. One of the major concerns during the machining of titanium alloy is the rapid tool wear and fracture of the tool due to high impact forces. In order to provide a better understanding of the influence of high pressure waterjet cooling/lubrication in improving tool life, detailed experiments were conducted. Figure 14 shows a plot of flank wear land vs cutting time. The flank wear vs time graph shows an expected behavior of rapid flank wear initially, followed by a relatively lower rate of flank wear in the later stages of cutting time. However, it can be seen that the tool life increased by 150% with the application

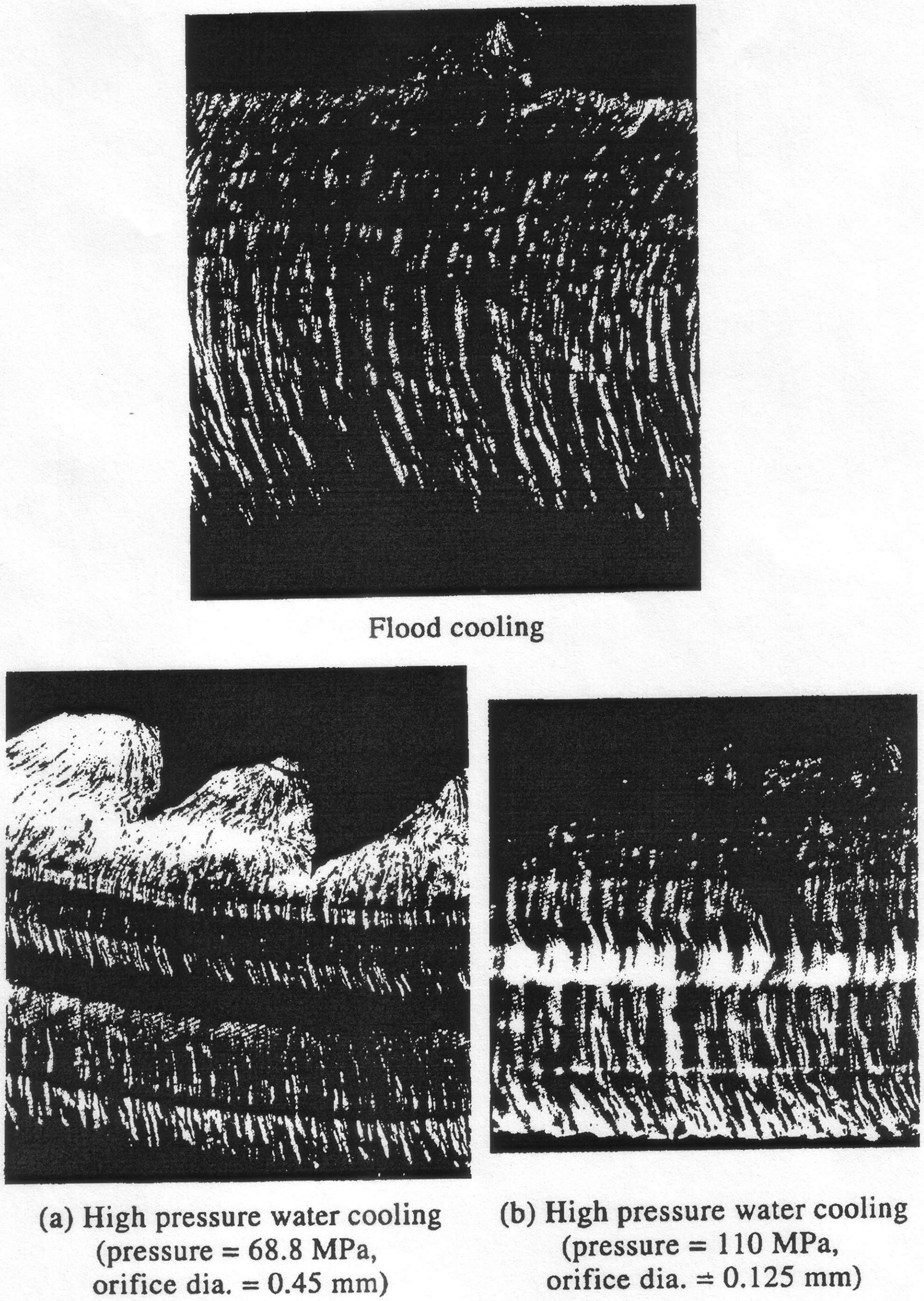
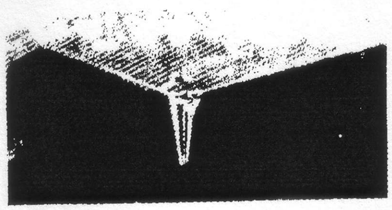


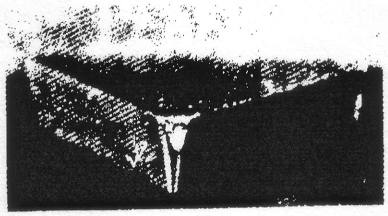

Fig. 10. SEM photographs of chips (50 ×).

of high pressure waterjet. With a further increase in water pressures, no significant improvement was registered in tool life.

The results obtained from this study show the capability of high pressure waterjet in improving the machining performance while machining difficult-to-machine materials like titanium. An improvement in the surface quality indicates an enhanced dimensional accuracy which is very crucial while manufacturing precision components for the aircraft industry. The quality of the surface obtained is fundamentally a geometric and kinematic



(a) High pressure water cooling (pressure = 68.8 MPa, orifice dia. = 0.125 mm)



(b) Flood cooling

Fig. 11. Photographs of wear of insert for (a) high pressure waterjet cooling and (b) flood cooling.

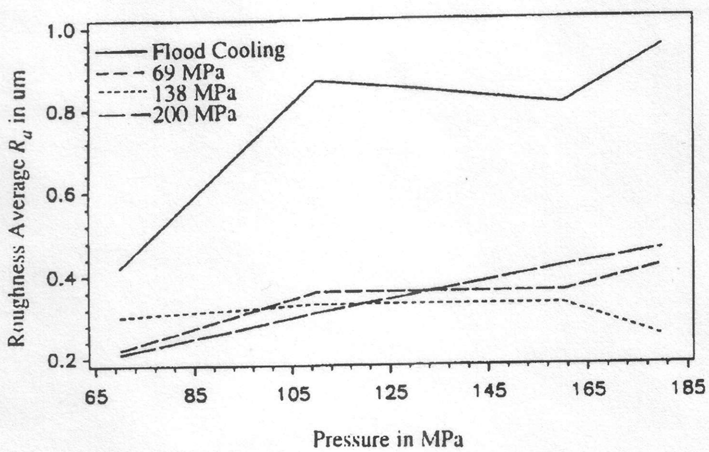



Fig. 12. Surface roughness ($R_a$) vs cutting speed.

reproduction of the cutting edge. As already stated, with the application of high pressure waterjet, the rate of tool wear is reduced which contributes to the improvement in surface finish. The high pressure waterjet serves to reduce the tool–chip contact area. This was evident from the fact that the chip size (which depends upon the tool–chip contact length) is much smaller at higher pressures. This reduced tool–chip contact length consequently serves to alleviate the severe thermal/frictional conditions at tool–chip interface. Similar to the results obtained in the case of supplying high pressure waterjet through the insert, here also, it was observed that after reaching a certain optimum value, a further increase in water pressure was not found to be very beneficial in further improving machining performance. This could be due to the reasoning that a high pressure waterjet after penetrating to a certain depth into the tool–chip interface is not capable of penetrating any deeper, overcoming the high

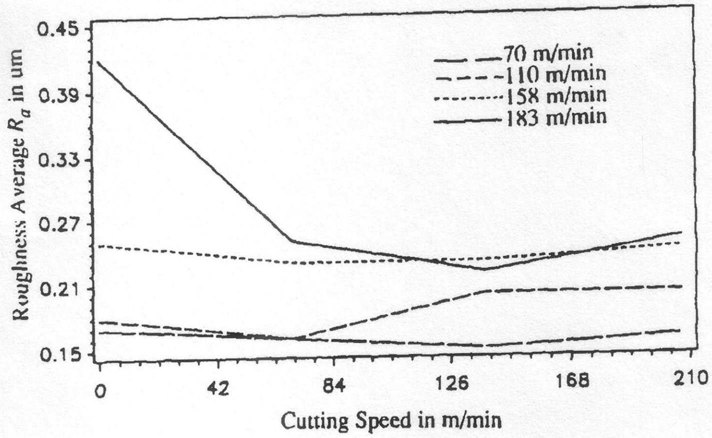



Fig. 13. Waterjet pressure vs ($R_a$).

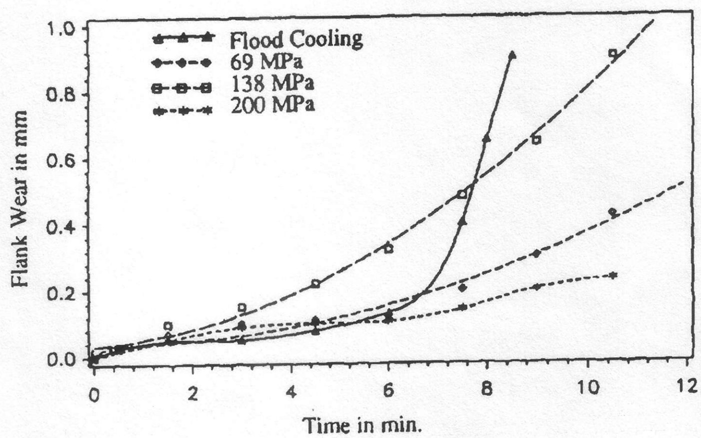



Fig. 14. Flank wear land vs cutting time.

contact pressures at the tool–chip interface. Further investigations need to be carried out to have a better understanding of this phenomenon.

## 4. SUMMARY AND CONCLUSIONS

This study led to the evaluation of the effectiveness of the two developed high pressure coolant/lubricant systems based upon two different methods of application of waterjet in conjunction with rotary tool operations (face milling and down milling). The feasibility of improving the machinability of difficult-to-machine materials was also explored in this study. The results clearly indicate the advantages of using high pressure waterjet cooling over flood cooling while machining these materials.

(1) There is a drastic reduction in the cutting forces required to remove material from the workpiece with the application of high pressure waterjet.

(2) The surface finish obtained with the use of high pressure waterjet in both the methods of application is much better than that obtained in the case of flood cooling. Under certain conditions, the surface finish obtained with the use of high pressure waterjet is comparable to that obtained in the case of grinding operation.

(3) The SEM photographs of chips produced while machining stainless steel clearly show intense shearing action in the case of flood cooling indicated by the big serrations which were relatively very small in the case of high pressure waterjet cooling.

(4) The welding of hot chip to the cutting edge which is a common problem while machining titanium is completely eliminated with the application of high pressure waterjet, leading to an improvement in surface quality and tool life.

(5) In the case of application of high pressure waterjet through the tool rake face, friction is reduced at the tool–chip interface due to formation of a cushion layer which prevents intimate contact at the tool–chip interface, consequently leading to bending and self-breakage of chips. Whereas in the case of high pressure waterjet through an external nozzle, tool–chip contact area is reduced due to the fragmentation of the chip by the impinging jet.

(6) Finally, the reduction in cutting force accompanied by improvement in tool life, surface finish, and chip shape with the use of a high pressure waterjet as a coolant/lubricant leads to improvement in the metal removal rate and consequently the efficiency of rotary tool operations especially in the case of difficult-to-machine materials.

(7) Further, the enhanced effectiveness of the coolant/lubrication by applying the cutting fluid at high pressures in the form of a narrow jet, leads to a reduction in the quantity of the cutting fluid being used, reducing the amount of disposal, which is a primary concern of Environmental Protection Authorities.

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