Evaluation of Ultrasonic Vibration Cutting while Machining Inconel 718

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Hard and brittle materials, such as Ni- and Ti-based alloys, glass, and ceramics, are very useful in aerospace, marine, electronics, and high-temperature applications because of their extremely versatile mechanical and chemical properties. One Ni-based alloy, Inconel 718, is a precipitation-hardenable material designed with exceptionally high yield strength, ultimate tensile strength, elastic modulus, and corrosion resistance with outstanding weldability and excellent creep-rupture properties at moderately high temperatures. However, conventional machining of this alloy presents a challenge to industry. Ultrasonic vibration cutting (UVC) has recently been used to cut this difficult-to-machine material and obtain a high quality surface finish. This paper describes an experimental study of the UVC parameters for Inconel 718, including the cutting force components, tool wear, chip formation, and surface roughness over a range of cutting conditions. A comparison was also made between conventional turning (CT) and UVC using scanning electron microscopy observations of tool wear. The tool wear measured during UVC at low cutting speeds was lower than CT. UVC resulted in better surface finishes compared to CT under the same cutting conditions. Therefore, UVC performed better than CT at low cutting speeds for all measures compared.

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NOMENCLATURE

a = tool vibration amplitude, μm
a_p = depth of cut, mm
F_a = axial force component, N
F_r = radial force component, N
F_t = tangential force component, N
f = tool vibration frequency, kHz
f_r = feed rate, mm/rev
r = tool-workpiece contact ratio
t = time, sec
V_B = flank wear width, mm
v_c = workpiece cutting speed, m/min
v_t = tool vibration speed, m/min
z = tool vibration displacement
ω = tool vibration angular velocity, rad/sec

1. Introduction

Ni- and Ti-based alloys, glass, ceramics, carbides, and hardened steels are defined as difficult-to-machine materials because of their unique and versatile mechanical and chemical properties.[1-5] One Ni-based super alloy, Inconel 718, was designed to have exceptionally high yield strength, ultimate tensile strength, fracture toughness, elastic modulus, and corrosion resistance with outstanding weldability and excellent creep-rupture properties at temperatures up to 700°C.[6] These high-grade properties make the alloy useful for different impact-resistant applications in pumps, gas turbines, rocket motors, spacecraft, nuclear reactors, and tooling. However, this alloy causes tool blunting, unusual tool wear, chatter vibration, and high cutting temperatures, resulting in cutting instabilities and poor machinability in conventional turning (CT) processes.[3,7] Therefore, high quality turned parts for various applications cannot be obtained using CT.

Ultrasonic vibration cutting (UVC) has been applied successfully over the last three decades to cut difficult-to-machine materials because of its low cutting force and high cutting stability.[3,4,8,9] In this cutting method, the tool cutting edge interacts with the workpiece for a certain time pulse during each cycle of vibration. The intermittent cutting decreases the number of micro-cracks on the finished surface and reduces the cutting forces, tool wear, and number of machining steps.[4,7,10] As a result, UVC saves manufacturing time while reducing the machining cost[4] and improves both the cutting quality and the productivity of the process.[4,10]

Many experiments have been performed using the UVC technique for different combinations of tool-workpiece material. Recently, Mitrofanov *et al.*[11] developed an advanced finite element (FE) model to study the effects of cutting parameters, such as feed rate, cutting speed, and depth of cut, for UVC of Inconel 718. However, an experimental investigation of this alloy with a cubic boron nitride (CBN) tool has not yet been performed. As a hard cutting tool material, CBN is the next best choice to diamond tools. The random orientation of crystals within a CBN blank results in uniform hardness and abrasion resistance in all directions. In addition, the combination of the toughness of the cemented tungsten carbide with the hardness of the CBN layer allows CBN cutting tools to withstand the cutting forces encountered when cutting tough, difficult-to-machine materials. Moreover, CBN tools are less expensive than diamond tools.

The objective of this study was to determine whether UVC can be used to efficiently machine Inconel 718 with CBN tools. An experimental study was performed to evaluate UVC for this tool-material combination. The results demonstrated how the output parameters, such as cutting force components, tool wear, chip formation, and surface roughness, varied with the input cutting parameters, such as feed rate, cutting speed, and cutting time. The tool wear evolution and chip generation under different cutting conditions were observed by scanning electron microscopy (SEM). The performances of UVC and CT were compared in terms of the cutting force, tool wear, and surface roughness. The findings indicated why UVC performed better than CT up to a certain cutting speed. However, beyond a given cutting speed, the CBN tools failed catastrophically during UVC due to the number of consecutive strong impacts between the tool and workpiece at high frequencies of tool vibration.

2. Experimental Setup and Procedure

All tests were performed with a CNC lathe machine (Okuma LH35-N). One end of the Inconel 718 workpiece 600 mm in length and 175 mm in diameter was clamped into the three-jaw chuck, while the other end was supported by the tailstock of the lathe. Ultrasonic vibration is a piezoelectric effect fed to the tool by a piezoelectric transducer (PZT) element. The experimental tool setup, including the PZT, is illustrated in Fig. 1 and was designed specially to study UVC.

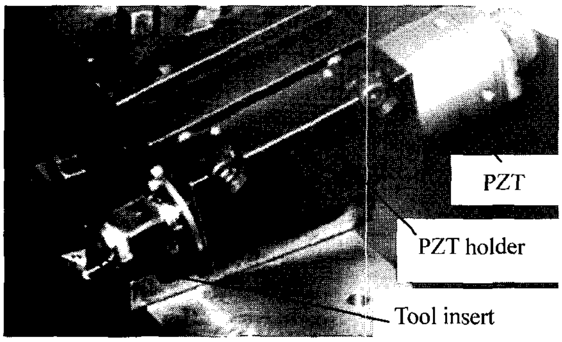


Fig. 1 Photograph of tool holder, including PZT, used for UVC

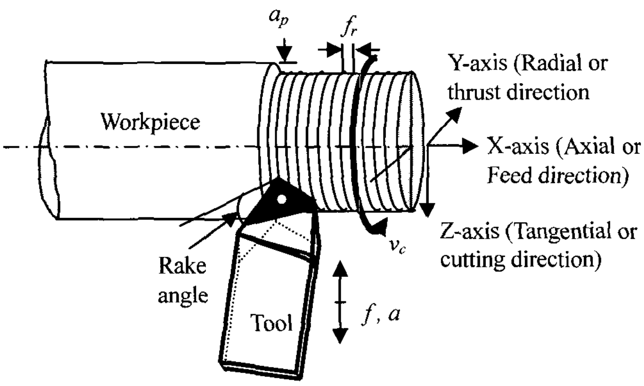


Fig. 2 Schematic diagram of the tool-workpiece contact mechanism in the tangential UVC system

The transducer can provide vibrations to the tool tip in three principle directions corresponding to the X, Y, and Z axes,[12] as shown in Fig. 2. The application of tangential or cutting directional vibrations along the Z axis is a common practice.[12] A fresh 60° triangular CBN tool insert (BN250) was mounted on the cutter head for each test.

A sonic impulse *SB-150* vibration device was used to induce vibrations in the cutting direction at the tool tip. This is also illustrated in Fig. 2. The available power source for the device was AC 100 V with a frequency of 50–60 Hz that consumed electric power at 260 VA. This device provided a frequency f of 19 kHz and an amplitude a of 15 μm. Assuming a sinusoidal motion for the tool displacement,

$$z = a \sin \omega t \tag{1}$$

Hence, the maximum vibration speed of the tool tip is

$$(v_t)_{\max} = 2\pi f a = 107.4 \text{ m/min} \tag{2}$$

Table 1 Specifications and properties of Inconel 718[13]

Percent chemical composition

Ni: 52.5	Ti: 1.0	Cu 0.09	B: 0.005
Cr: 18.6	C0: 0.24	Mn: 0.07	P: < 0.005
Nb: 5.43	Al: 0.6	C: 0.031	S: 3 ppm
Mo: 3.09	Si: 0.11	Ta: < 0.02	Fe: Balance

Mechanical properties at room temperature

Ultimate tensile strength:	1252 MPa
Yield strength (0.2% off.):	932 MPa
Elongation on 36.5 mm:	25.5%
Reduction of area:	30%
Hardness:	352 HB
Impact energy (Charpy test):	75–77 J

Table 2 Experimental conditions

Tool (triangular)	
Material:	CBN (BN250)
Rake angle:	+10°
Relief angle:	11°
Approach angle:	30°
Nose radius:	0.4 mm
Workpiece	
Material:	Inconel 718
Diameter:	175 mm
Cutting conditions	
Depth of cut:	0.10 mm
Feed rate:	0.025 to 0.1 mm/rev
Cutting speed:	5 to 20 m/min
Vibration conditions	
Frequency:	19 ± 1.5 kHz
Amplitude:	15 μm

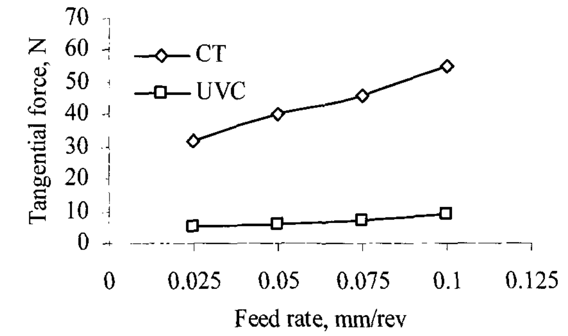
Table 1 shows the elemental composition and mechanical properties of the Inconel 718 workpieces tested in this study. The experimental conditions are shown in Table 2. The same test conditions were used for both CT and UVC. The depth of the cut was set to 0.1 mm and the tool rake angle was +10°. Machining was stopped at regular intervals (about 2 min) during one pass to measure and observe the output parameters, such as cutting force components, flank wear width, chip formation, and surface roughness. Burrs formed on the workpiece surface were removed after each cut. To separate the types of vibration cutting, the cutting speeds for all tests were less than the maximum vibration speed given in Table 2.

3. Results and Discussion

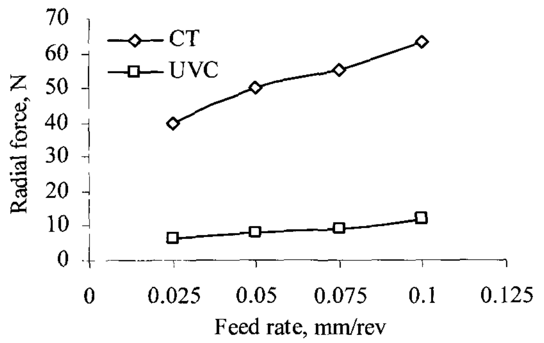
3.1 Cutting force *vs.* feed rate

A Kistler three-component tool dynamometer was used to measure the cutting force components in the tangential, radial, and axial directions. The force signals were measured with a Graphtec chart recorder.

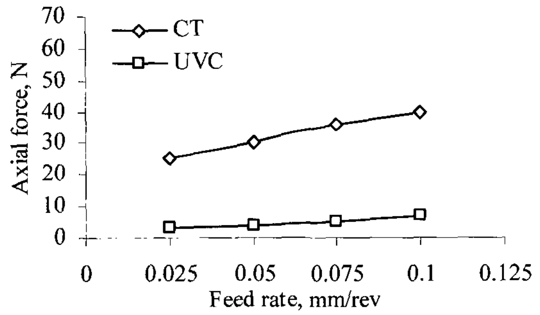
Figure 3 shows the cutting force components for a range of feed rates at a cutting speed of 10 m/min using both CT and UVC to machine the Inconel 718 specimens. As expected, the cutting force increased with the feed rate for both cutting processes, which means that UVC follows the same rules as CT. All the UVC force components at all feed rates examined were reduced to approximately 12–20% of the CT force components. However, the rate at which the UVC cutting forces increased with the feed rate was small, unlike the CT cutting forces.



(i) Tangential cutting force *vs.* feed rate



(ii) Thrust cutting force *vs.* feed rate



(iii) Axial cutting force *vs.* feed rate

Fig. 3 Cutting force *vs.* feed rate for both CT and UVC at a cutting speed of 10 m/min

As the UVC technique steps forward using a number of passes for the same area of the workpiece, the actual depth of cut for each pass is smaller and hence the cutting load at the tool nose for each of the three components should theoretically be lower compared to the single-pass cutting action in CT. In addition, the UVC tool-workpiece contact ratio (discussed in Section 3.5) is less than unity, which assists in keeping the force components low. This explains the lower rate at which the UVC cutting forces increased with the feed rate in Fig. 3.

The thrust or radial cutting force was the greatest force component, followed by the tangential cutting force, while the axial or feed force was the smallest. In general, a tangential or cutting component is greater than the thrust component for positive rake angle tools, smaller for negative rake angle tools, and equal for zero rake angel tools. However, during ultra-precision cutting of brittle materials using tools with an edge radius, the effective rake angle becomes negative, causing the thrust force to be greater than the tangential force[14]. This was the cause for the CBN tool used in these tests. In addition, the CBN tool began to wear from the start of cutting Inconel 718, decreasing the edge sharpness of the tool and causing the tool nose to have a more flattened profile. Therefore, the thrust was the greatest force component.

3.2 Tool wear *vs.* feed rate

The width of the tool wear along the flank V_B was measured with a toolmaker's microscope. Figure 4 shows the measured tool wear *vs.* the feed rate after 10 min of machining for both cutting methods at a cutting speed of 10 m/min. The flank wear for CT increased suddenly when the feed rate shifted from 0.025 mm/rev to 0.05 mm/rev; it maintained a steady rate of increase at higher feed rates. In contrast, the tool wear during UVC increased linearly with a small slope throughout the entire range of feed rates examined. It is clear that the tool wear rate in CT was significantly higher than that in UVC.

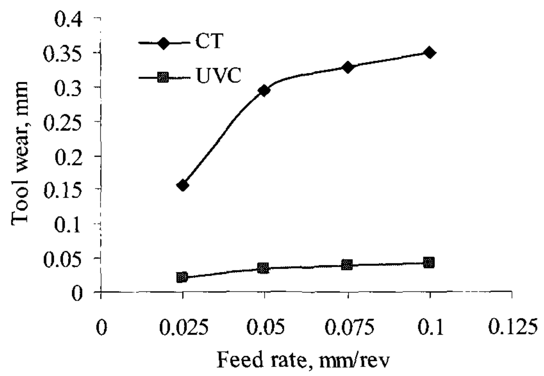


Fig. 4 Experimental tool flank wear width values (V_B) against feed rate at a cutting speed of 10 m/min after 10 min of cutting

Due to the small UVC force components discussed in Section 3.1, the UVC tool wear rate also increased slowly and steadily in this method as compared to CT. The force components were decreased further by the reduced tool wear. Therefore, the low UVC tool wear rate improved the cutting stability and prolonged the tool life. At all feed rates examined, the UVC tool wear was 12–14% less than that for CT. According to these results, the tool life for UVC is 7–8 times longer than that for CT.

3.3 Cutting force *vs.* cutting speed

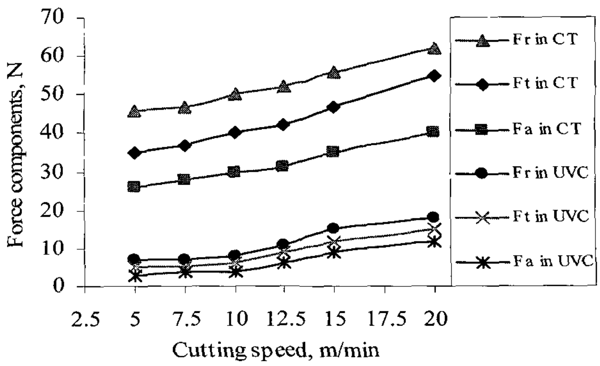


Fig. 5 Cutting force components *vs.* cutting speed at a feed rate of 0.05 mm/rev for both cutting processes

Figure 5 shows the influence of the cutting speed on the cutting force components for both cutting techniques at a feed rate of 0.05 mm/rev. Similar to the previous cases, the UVC cutting force components were reduced from 12–25% as compared to CT at all cutting speeds examined.

The lower cutting force encountered during UVC was mainly due to the small amount of built-up edges (BUEs), the consequent material reduction during the tool upward motion,[15] and the separation or pulse cutting characteristics of the tool. The smaller depth of cut during each pass of UVC also reduced the material cutting load at the tool nose. This explains why the UVC force components decreased as compared to CT.

3.4 Tool wear *vs.* cutting speed

Tool flank wear curves at different cutting speeds are shown in Fig. 6. Initially, the CT tool wear rate increased with the cutting speed as the cutting load at the tool edge and tool nose increased. Although the tool wear rate was greater for CT than for UVC, the CT cutting operation was possible for all cutting speeds examined. The UVC tool wear remained low and relatively constant up to a cutting speed of 10 m/min after 10 min of cutting. Beyond this point, the tool nose experienced a high rate of tool wear and failed after only 4 min of cutting at 15 m/min. In contrast, a relatively low CT wear rate was observed even after 10 min of cutting.

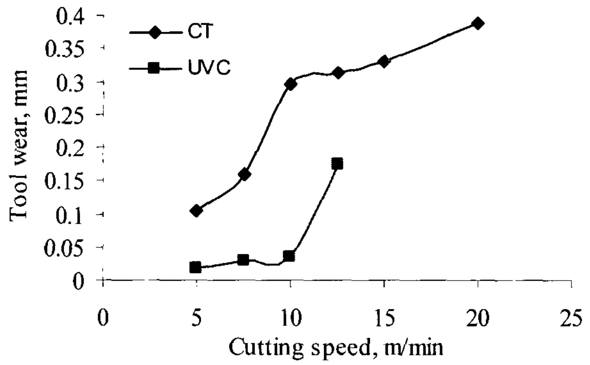
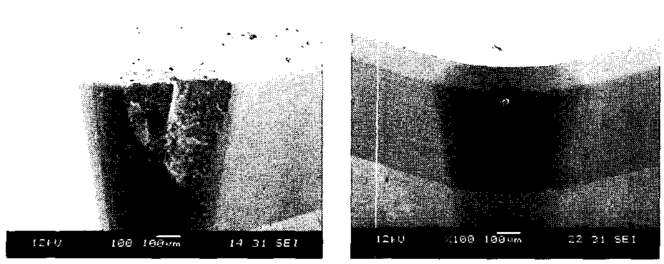


Fig. 6 Tool flank wear (V_B) *vs.* cutting speed for both cutting processes after 10 min of cutting at a feed rate of 0.05 mm/rev



(i) 10 m/min, CT (ii) 10 m/min, UVC

(iii) 15 m/min, CT (iv) 15 m/min, UVC

Fig. 7 SEM photographs of the tool wear behavior for different cutting conditions at a feed rate of 0.05 mm/rev

Figure 5 showed that the CT cutting force components increased linearly with the cutting speed. However, a sudden change in the UVC cutting force components was observed when the cutting speed shifted from 10 to 15 m/min because the relative speed between the tool and workpiece as well as the tool-workpiece contact time increased with the cutting speed. This high relative speed and the number of consecutive strong impacts over a relatively long period damaged the nose and edge on the rake face of the tool. As Inconel 718 has excellent toughness, the tool material could not withstand these high impacts for long periods.

The flank wear characteristics of the tools used in the tests were examined by SEM. The photographs shown in Fig. 7 illustrate the CBN tool wear when cutting Inconel 718 using both cutting techniques at two significantly different cutting speeds. The tool used for UVC failed catastrophically along the cutting edge starting from the tool nose after 4 min of cutting at 15 m/min. Due to the worsening tool condition, the measured cutting force components increased sharply as the cutting speed shifted toward higher values.

3.5 Tool wear *vs.* cutting time

The tool wear characteristics were also observed as functions of the machining time for both cutting methods at a feed rate of 0.05 mm/rev. The machining was stopped at regular intervals (about 2 min) in one pass to measure the flank wear width of the tool.

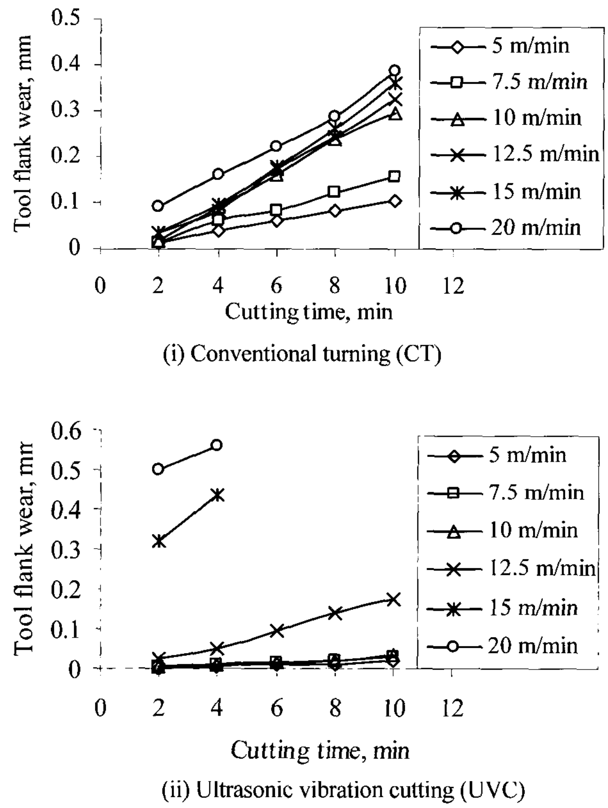


Fig. 8 Tool flank wear width (V_B) *vs.* cutting time for both cutting methods at a feed rate of 0.05 mm/rev

The UVC tool wear rate was substantially lower than that of CT up to a cutting speed of 10 m/min as the UVC tool-workpiece impacts were small and the UVC tool-workpiece contact time was low. Xiao *et al.*[8] established the following equation for $2\pi af > v_c$ by combining basic UVC relationships:

$$v_c(1 - r) = 2af \sin \pi r \cos[\cos^{-1}(-v_c/(2\pi af)) - \pi r] \tag{3}$$

This equation can be used to determine the relationship between the UVC tool-workpiece contact ratio r and the cutting speed v_c, as shown in Fig. 9. The UVC tool-workpiece contact ratios were 0.1739 and 0.2163 at cutting speeds of 10 and 15 m/min, respectively, for an ultrasonically vibrated tool at a frequency of 20 kHz with an amplitude of 15 μm. Therefore, the tool-workpiece contact ratio increased with the cutting speed.

Small UVC contact durations favored low tool wear rates. The CT wear rate was higher due to the continuous cutting process (*i.e.*, 100% tool-workpiece contact time), which caused a temperature rise and different wear mechanisms at the contact area, leading eventually to elastic and plastic deformation.

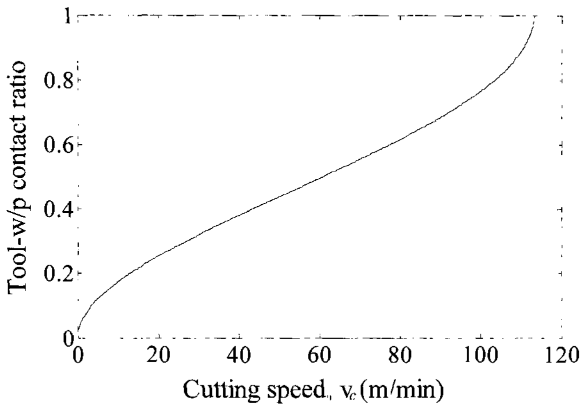
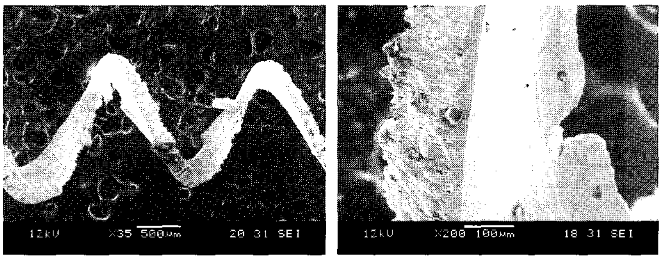


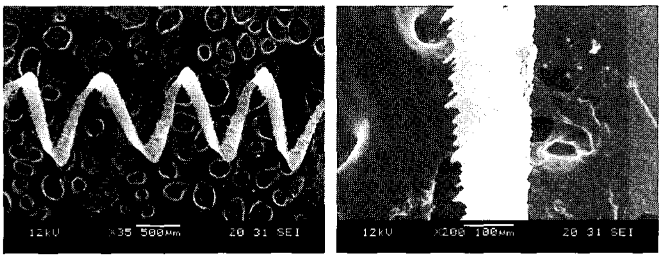
Fig. 9 Relationship between the UVC tool-workpiece contact ratio r and the cutting speed v_c

3.6 Chip formation observations

The chips produced by both CT and UVC were analyzed on SEM photographs showing the types of chips obtained using the same cutting conditions for both methods (see Fig. 10).



(i) 10 m/min, 0.05 mm/rev, CT



(ii) 10 m/min, 0.05 mm/rev, UVC

Fig. 10 SEM photographs of chips formed at different cutting speeds for both cutting methods at a feed rate of 0.05 mm/rev

UVC always produced thin, smooth, and long chips. In contrast, CT generated comparatively thick, uneven, short, and cracked chips under the same cutting conditions. The chip thicknesses for UVC and CT were approximately 0.15 and 0.30–0.40 mm, respectively, at a cutting speed of 10 m/min and a feed rate of 0.05 mm/rev. Thicker and uneven chips are always unfavorable for high-quality machining. An increase in the chip thickness while machining produces higher cutting forces. In addition, uneven, thick, and cracked chips induce high regenerative chatter and rapid tool wear. These types of chips subject the tool cutting areas, including the tool nose, cutting edge, and rake face, to non-uniform friction and generate higher temperatures.

3.7 Surface roughness *vs.* feed rate

The surface roughness, which identifies the quality of the finished surface, is one of the main concerns of manufacturing industries. The achievement of a high-quality surface finish for difficult-to-machine materials is a major concern related to the use of the UVC process. A *Surtronic 10* surface analyzer was used to measure the surface roughness throughout the tests. The results are shown in Fig. 11.

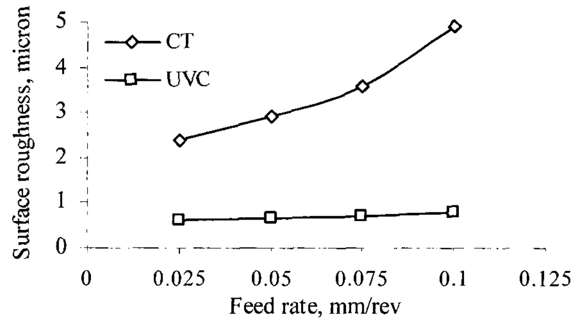


Fig. 11 Measured surface roughness values *vs.* feed rate at a cutting speed of 10 m/min for both cutting methods

It is generally true that the surface finish degrades with increasing feed rate; this was the case for the data shown in Fig. 11. For all the cutting conditions examined, UVC resulted in lower roughness values as compared to CT. A rough and coarse surface finish was generated by CT at higher feed rates. When machining Inconel 718 at a cutting speed of 10 m/min, CT achieved minimum and maximum surface roughnesses of 2.4 μm and 4.9 μm, respectively, whereas UVC achieved minimum and maximum surface roughnesses of 0.6 μm and 0.8 μm, respectively. Thus, the UVC surface roughness had little variation with the feed rate, unlike CT. These observations indicate that a high-quality surface finish can be achieved on difficult-to-machine materials using the UVC method.

3.8 Surface roughness *vs.* cutting speed

The surface roughness increased with the cutting speed at a feed rate of 0.05 mm/rev, as shown in Fig. 12. The values shown in Fig. 12 were measured after 10 min of machining. Values for UVC at cutting speeds of 15 m/min and 20 m/min are not shown as the tool wore out quickly under these conditions. The UVC surface roughness was reduced by 20–25% as compared to CT at a feed rate of 0.05 mm/rev. At cutting speeds between 5 and 10 m/min, surface roughness values of 0.60–0.65 μm were achieved with UVC, while surface roughness values of 2.3–2.9 μm were achieved with CT. The UVC roughness values did not increase significantly with the cutting speed, unlike CT.

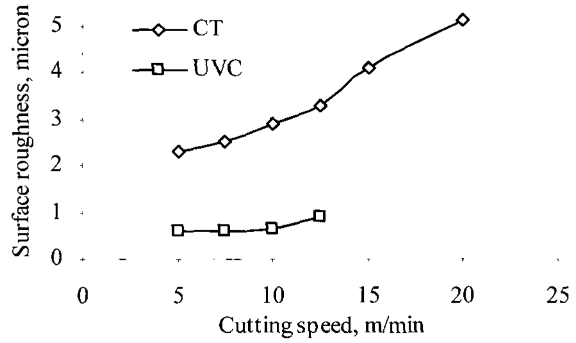
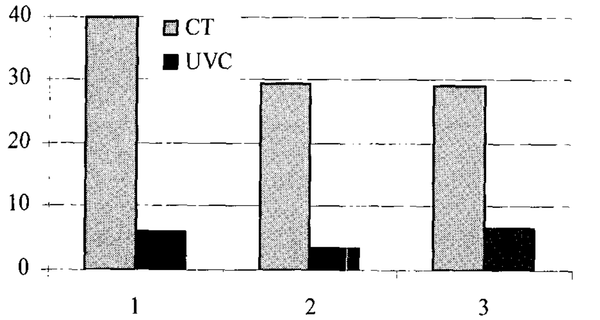


Fig. 12 Measured surface roughness values *vs.* cutting speed at a feed rate of 0.05 mm/rev for both cutting methods

The variation of the surface roughness during cutting is related to many variables. During CT, the machined surface deteriorated with the generation of thick, uneven, and severely cracked chips, BUEs, high cutting force components, frictional heat, and high cutting instabilities because the tool edge and workpiece were always in contact. The chips generated by CT (see Fig. 10) always left unusual pits in the cutting edge area, as shown in Fig. 7, that also affected the surface roughness of the finished workpiece. In contrast, the same figures show that UVC produced comparatively sharp, fine chips that had less influence on the workpiece surface. As BUEs occurred rarely, the surface finish obtained with UVC was regular and smooth.

3.9 Comparative analysis between CT and UVC

The results of a comparative analysis between CT and UVC are presented in Fig. 13. As UVC performed remarkably better at 10 m/min, this cutting speed was selected as the most suitable for comparative analysis of turning Inconel 718 at 0.05 mm/rev. The output parameters used for the comparison were the tangential cutting force component, width of flank wear, and surface roughness.



1) Tangential force in N, 2) Width of tool flank wear in mm x 100 and 3) surface roughness in mm x 10

Fig. 13 Comparative analysis of the cutting performance of CT and UVC at a feed rate of 0.05 mm/rev

The columns shown in Fig. 13 clearly indicate that UVC performed considerably better than CT for all cases. UVC not only attained high-quality cuts in a difficult-to-machine material, but also increased the tool life significantly and reduced the machining cost.

4. Conclusions

The performance of UVC was evaluated and compared with that of CT using the same cutting conditions to machine the Ni-based alloy, Inconel 718. The cutting force components, tool flank wear width, chip formation, and surface roughness were used in the evaluation. The following conclusions can be drawn based on the results of this study.

1. UVC required a cutting force that was 12–25% less than the CT cutting force when machining Inconel 718.
2. The UVC tool wear was reduced by 12–14% as compared to CT when cutting up to a speed of 10 m/min at a feed rate of 0.05 mm/rev and a depth of cut of 0.1 mm. As a result, the tool life for UVC was increased by 7–8-fold.
3. Due to consecutive passes of the tool over the workpiece, UVC produced thinner and more even chips, which reduced both the cutting forces and the tool wear.
4. UVC produced a surface roughness ranging from 0.6–0.8 μm, whereas CT produced a minimum surface roughness of 2.4 μm.
5. The tools failed catastrophically after 4 min of UVC when the cutting speed exceeded 10 m/min due to the number of consecutive strong impacts as well as the comparatively long duration of the tool-workpiece interaction at these speeds.
6. Even though the UVC method has major cutting speed limitations when used for difficult-to-machine materials, it is a suitable method for achieving a high-quality surface when working with Inconel 718.

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