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Effect of hybrid machining on structural integrity of aerospace-grade materials

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Abstract

Aerospace-grade alloys such as Inconel 718 are widely used in the airspace industry primarily thanks to their excellent mechanical properties at high temperatures. However, these materials are classified as 'difficult-to-machine' due to their high shear strength, tendency to work-harden and presence of carbide particles in their microstructure, which lead to rapid tool wear. In addition, low thermal conductivity of Inconel 718 requires appropriate thermal management to prevent temperate-induced tool failure. Post-machining, it is important to assess structural integrity of machined parts. Machining-induced residual stresses in the machined part is an important parameter as it can be used to assess overall structural resilience and the propensity of a part to suffer fatigue failure. To improve structural integrity of machined parts, various non-conventional machining techniques have been introduced over the years. Ultrasonically assisted turning (UAT) is a hybrid machining technique, in which tool-workpiece contact conditions are altered by imposing ultrasonic vibration (typical frequency ~20 kHz) on a cutting tool's movement in a cutting process. Several studies demonstrated successfully the resulting improvements in cutting forces and surface topography. However, a thorough study on UAT-induced residual stresses is missing. In this study experimental results are presented for machining Inconel 718 using both conventional turning (CT) and UAT with different cutting speeds to investigate the effect on cutting forces, surface roughness and residual stresses in the machined parts. Our study indicates that UAT leads to significant cutting-force reductions and improved surface roughness in comparison to CT for cutting speeds below a critical level. The residual stresses in machined workpiece show that UAT generates more compressive stresses and reduces tensile stresses when compared to those in CT. Thus, UAT improves the overall machinability of Inconel 718.

Keywords: Ultrasonically assisted turning; Machinability; Residual stress; Service performance; Inconel alloy

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Introduction

Aerospace-grade alloys such as Inconel 718 are extensively used in the airspace industry primarily because of their excellent mechanical properties at high temperatures [1]. However, poor machinability of Inconel 718 makes it difficult-to-machine due to its low thermal conductivity, ability to work-harden and its tendency to adhere to tool material [2].

Components made of this Ni-based alloy are expected to work in severe environments, thus, assessing structural integrity becomes essential. Surface topography, and residual stress are important to define component quality [3]. It is well documented that residual stresses contribute directly to premature failure of components [4].

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Ultrasonically assisted turning (UAT) is a promising hybrid machining process enhanced significantly in comparison with conventional turning (CT) techniques that yields improved machinability of various difficult-to-machine materials [5-10] as well as improved tool performance [11]. However, few researchers studied the effect of residual stresses of machined components produced with UAT. Sharma and Pandey [12] reported the effect with machining and vibration parameters on residual stresses in UAT of 4340 hardened steel. Nestler and Schubert [13] studied surface properties in UAT of particle-reinforced aluminium-matrix composites. Ahmed et al. [14] investigated hardness and residual stresses under machined surface in UAT of Inconel 718. Nanoindentation analysis demonstrated that the level of hardness of the surface layer in UAT was less than that in CT and closer to the hardness of the bulk material, which was also validated by Bai et al. [15]. However, they reported that the residual stresses in UAT were higher in comparison to CT. To the best of the authors' knowledge, no experimental investigation of residual stresses in UAT was carried for Inconel alloy.

In the current work, experimental investigation of machinability, especially for residual stresses generated by UAT in Inconel 718 is performed. Section 1 describes the experimental work, including details of the setup; and tools used, workpiece properties and experimental methodology. Experimental results such as cutting forces, surface topography and residual stresses are discussed in Section 2. The paper ends with some concluding remarks in Section 3.

1. Experimental setup and procedures

All experiments were performed on a modified lathe with the capability of CT and UAT as shown in Fig. 1. A coated cemented-carbide tool (DCMT 11T304-MF1105) was fixed on the ultrasonic machining device, which generated mechanical vibration with a frequency, f, of 18.11 kHz and peak-to-peak amplitude, A_{pp}, of 8.4 μm. A three-component Kistler dynamometer (Type 9257B) was employed to measure the cutting forces. Since the acquisition frequency of the dynamometer (of 3.5 kHz) is much lower than the imposed ultrasonic frequency, the measured cutting forces were essentially averaged over time. Cutting forces in tangential, radial and feed direction represent the cutting, thrust and feed forces of the cutting tool.

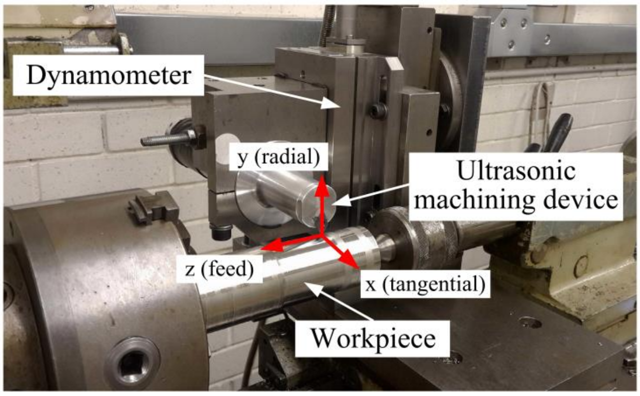

Fig. 1. Experimental setup of ultrasonic machining assembly.

Inconel 718, a high-strength corrosion-resistant nickel-chromium material, was used in our studies.

Several experiments were carried out by varying the cutting speed, feed rate, depth of cut and vibration amplitude as listed in Table 1.

Table 1. Cutting conditions of turning experiments.

Exp. No	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Vibration amplitude (μm)
1	20	0.08	0.12	8.4
2	30			
3	40			
4	20	0.16		
5		0.25		
6		0.08	0.20	
7			0.28	
8			0.12	6.7
9				4.9

Cutting forces were recorded for each experiment and averaged to assess the nominal cutting force for each machining condition. Surface topography of the machined surface was analysed with an Alicona InfiniteFocus system. Residual stresses on the surface of as-turned samples were measured for both CT and UAT using an X-ray diffraction (XRD) based technique. The measurements were carried out with Bruker D8 discover using Co Kα radiation operating at 40 kV and 40 mA. A $\sin^2\psi$ method was used for calculation of uniaxial residual stress.

2. Results and discussion

2.1 Cutting forces

The measured levels of cutting forces were compared in CT and UAT for various machining parameters (Fig. 2). Each set of machining parameter was carried out with axial turning with a distance of ~6 mm on the workpiece. Maximum and minimum forces obtained from a time-averaged cutting force plot were presented. Application of ultrasonic vibration brought a significant reduction in cutting forces, especially for the tangential force component. For cutting speed of 20 m/min, which is less than the calculated critical speed $\pi f A_{pp}$ (=28.7 m/min), a noticeable reduction in all force components was observed (Fig. 2(a)). The cutting force in CT decreased with an increase in the cutting speed from 20 m/min to 40 m/min. In contrast, the cutting force in UAT increased which an increase in the cutting speed from 20 m/min to 30 m/min, since higher speeds imply more tool time contact (less separation) for each vibratory cycle of the tool. When the cutting speed exceeds the critical speed, UAT essentially reduces to a CT process as tool separation vanishes completely. Thus, the extent of decline for cutting force with ultrasonic vibration decreased from 53% at 20 m/min to 22% at 30 m/min and 17% at 40 m/min. Analysis of varying the feed rate indicated, that the cutting and thrust forces in both CT and UAT increased with an increase in the feed rate (Fig. 2(b)). However, the decline of the cutting force reduced form 53% at 0.08 mm/rev to 29% at 0.16 mm/rev and 18% at 0.25 mm/rev. With an increase in the depth-of-cut, a similar trend for the cutting force was observed (Fig. 2(c)). The reduction of cutting force for greater depth of cut at 0.2 mm and 0.28 mm were only 25% and 28%, respectively. The effect of varying the vibration amplitude is shown in Fig. 2(d), where amplitude of 0 μm represents the CT process. Apparently, a reduction of cutting forces increased with an increase in the imposed vibration amplitude. In summary, an optimized set of machining parameters exists, with the cutting speed less than the critical speed, low feed rate and depth-of-cut with a large superimposed amplitude, to yield the highest force reductions in turning of Inconel 718.

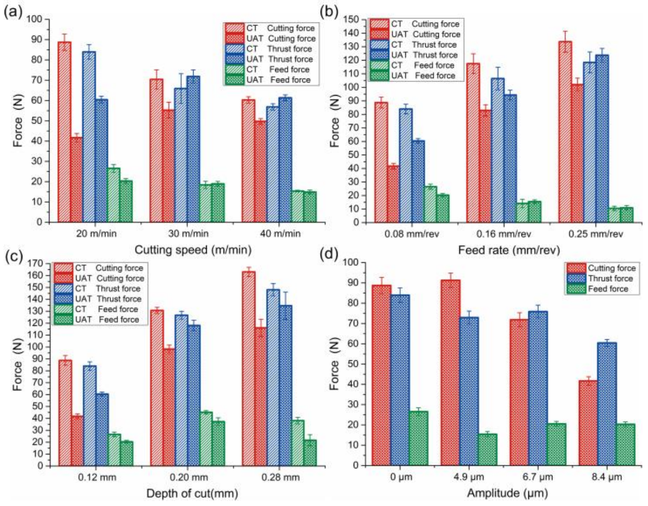

Fig. 2. Cutting forces in CT and UAT for various machining parameters.

2.2 Surface roughness and topography

As an important indicator of surface quality, surface roughness of a finished component was assessed by repeating the measurements at least three times to obtain averages and standard deviation. Comparison of surface roughness *Ra* for both CT and UAT with different machining parameters is shown in Fig. 3. Based on the measurements in Fig. 3(a), surface roughness increased slightly in CT and UAT with an increase in the cutting speed from 20 m/min to 40 m/min. When varying the feed rate, the magnitude of *Ra* increased significantly for both CT and UAT (Fig. 3(b)). In addition, the reduction of *Ra* with ultrasonic vibration decreased from 47% at 0.08 mm/rev to 34% at 0.16 mm/rev, then 17% at 0.25 mm/rev. This is due to the fact that the lower feed rate induced a shorter distance of adjacent tool path and lower residual height, which ultimately reduced greatly due to the polishing effect (the reciprocating motion of tool flank on the machined surface) in UAT. The depth-of-cut did not affect surface roughness visibly in CT (Fig. 3(c)). But for UAT, a larger depth-of-cut led to higher surface roughness. Thus, the reduction for machining with ultrasonic assistance reduced to 25% at 0.28 mm. For the varying vibration amplitude, the comparison of surface roughness is shown in Fig. 3(d). It is evident that the larger amplitude led to a greater reduction of surface roughness.

Surface topography of machined samples was observed with laser microscope and the 2D fields are shown in Fig. 4. The colour bars demonstrate that UAT produced lower average residual height of the machined surface.

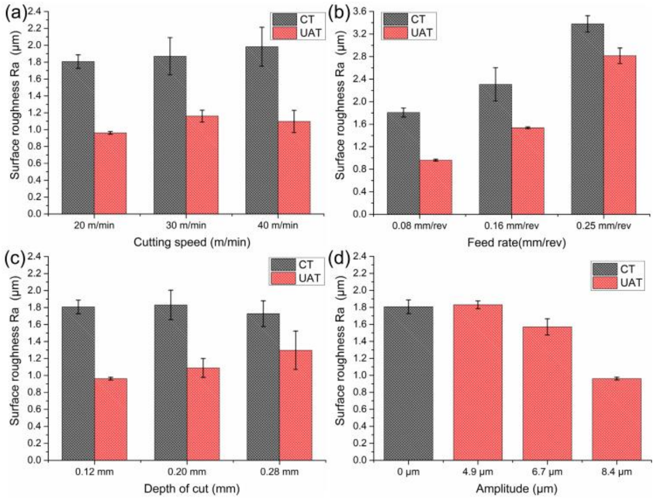

Fig. 3. Surface roughness in CT and UAT for various machining parameters.

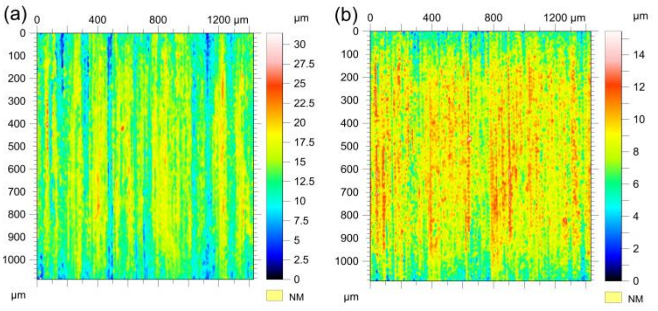

Fig. 4. Comparison of surface topography in: (a) CT; (b) UAT.

2.3 Residual stresses

Residual stresses were measured using XRD on the machined sample surface; the detailed results are given in Fig. 5. Five different incident angles were measured in each test and stress was determined by the $\sin^2\psi$ method. The gradient of the inter-planar spacing vs. $\sin^2\psi$ curve showed a good linear relationship in each test. Tensile residual stresses were generated during both CT and UAT of Inconel 718 alloy. At a cutting speed of 20 m/min, feed rate of 0.08 mm/rev and depth-of-cut of 0.12 mm the tensile residual stress of 769.7 MPa was measured in CT. In contrast, the application of ultrasonic vibration at 8.4 μm led to a lower tensile residual stress of 435.9 MPa. Thus, UAT can reduce the tensile residual stress of machined surfaces for Inconel 718 alloy, improving their fatigue resistance. The microcipping action of the cutting tool during UAT probably induces compressive stresses during the machining process thus reducing the otherwise tensile residual stress from standard turning operations. Additionally, other vibration modes may have been excited with the driving frequency, generating small-amplitude vibrations in the radial and feed directions. It is known that mechanical impacts in radial direction can cause compressive residual stress. Consequently, the lower tensile residual stress was measured on machined surface in UAT.

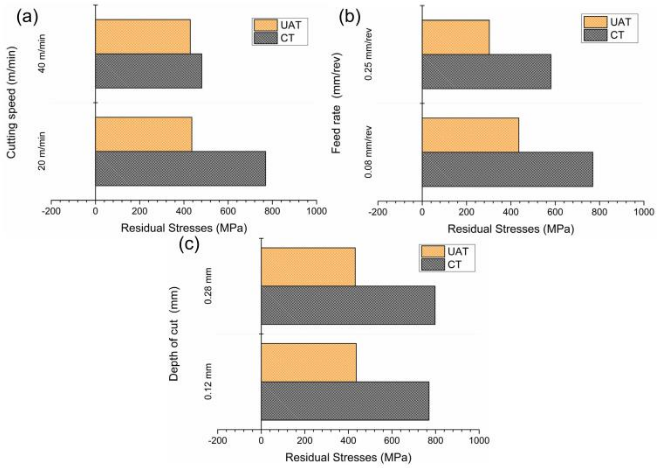

Fig. 5. Influence of parameters on residual stress in CT and UAT.

A reduction of tensile residual stresses was obtained with the increasing cutting speed in CT (Fig. 5(a)). However, the residual stress was maintained at various cutting speeds in UAT. A decline of surface residual stresses with various feed rates in both CT and UAT is shown in Fig. 5(b). A higher feed rate led to a larger cutting force (Fig. 2(b)), thus mechanical loading generated more compressive residual stresses. Fig. 5(c) shows that no visible changes of residual stresses occurred with a varying depth-of-cut in both CT and UAT, as many researchers reported with other materials [16, 17].

3. Conclusions

A study of the effect of a hybrid machining technique with ultrasonic vibration on machinability and structural integrity of Inconel 718 alloy was performed with various machining parameters. Noticeable improvements in machinability of Inconel 718 were obtained using UAT. The major conclusions of the study are as follows:

- Appropriate machining parameters, with a cutting speed below the critical speed, a low feed rate and a depth-of-cut along with higher vibration amplitude can reduce the cutting force significantly in UAT.
- UAT improves surface roughness notably for various machining parameters. The reduction of surface roughness by UAT decreases with increases in the feed rate and the depth-of-cut.
- From an XRD analysis, UAT generates more compressive stresses and reduces the overall tensile stresses when compared to those in CT.

Acknowledgements

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