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Investigation of critical edge radius effect for the variation of ultra-precision machining results of difficult-to-cut materials

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Abstract

The effects of properties of difficult-to-cut materials on the behaviour of critical cutting tool edge radius for the variations of machining results have been investigated. In ultra-precision machining, when undeformed chip thickness (*a*) becomes smaller than cutting tool edge radius(*r*), the governing parameter identified as relative tool sharpness, *RTS* (*a/r*). At smaller *RTS*, with highly negative effective rake angle, the intense compressive stress of the rounded cutting edge transforms material removal phenomena from shearing to "extrusion-like" deformation mechanism. The variations of machining forces, surface finishing, material flow stress, microchip morphology and surface microstructure quantifies the effective machining performance of the difficult-to-cut materials like Ti6Al4V alloy and Inconel 625. The results of this study will enhance the current knowledge of precision to ultra-precision machining industries to support the emerging fields of aerospace, electro-mechanical, oil field and biomedical applications.

Cutting edge radius effect, ultra-precision machining, difficult-to-cut materials, Ti6Al4V, Inconel 625

1. Introduction

Titanium and Nickel alloys are widely used in aerospace, biomedical, automotive and petroleum industries [1-2]. However, precision machining is difficult due to low Young's modulus of Ti and work hardening characteristics of Ni alloys. Moreover, dry machining of Ti and Ni alloys is getting emphasis for sustainable manufacturing [3]. Furthermore, possibility of machining as a surface enhancement tool by avoiding expensive secondary processes has not been critically investigated yet [4]. Moreover, cutting tool edge preparation is getting priority now a day [5]. In fact, cutting edge radius effect is one of the factors causing the variation of the surface generation process in ultra-precision machining. To analyse edge radius effect, the governing process parameter identified as ratio of undeformed chip thickness (*a*) to edge radius (*r*), known as relative tool sharpness, *RTS* (*a/r*). In this study, orthogonal machining of difficult-to-cut materials have been emphasized with influencing factor of critical edge radius effect.

2. Material, cutting tool and experimental methodology

Hollow cylindrical workpieces (75 mm OD, 1 mm wall thickness) were used for the experiment under dry condition as shown in Fig. 1. The chemical compositions are listed in Table 1.

Table 1 (Chemical composition)

Alloy/Comp (%)	Al	V	Fe	Cr	Ni	Ti
Ti6Al4V	6.2	4.1	0.1	-	-	Bal
Inconel 625	0.2	-	3.5	22.2	60.4	-

High strength CBN (7° relief, -25° rake) was utilized as cutting insert with measuring of edge radius (*r*) in confocal microscope. During experiment, federate was varied to achieve undeformed chip thickness (*a*) with cutting speed (*V*) as per eqn (1).

$$f = \frac{V*1000*RTS*r}{\pi*60*OD} \qquad \text{----------------- (1)}$$

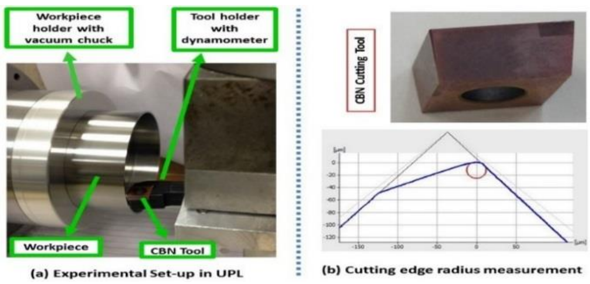

Figure 1. Orthogonal micro turning process with CBN tool

3. Results and discussions

3.1. Analysis for Inconel 625

Thrust oriented micro cutting mechanism observed for Inconel 625 as thrust force (F_t) is almost 2 times of cutting force (F_c), as illustrated with variation of force ratio (F_t/F_c) with *RTS* in Fig. 2.

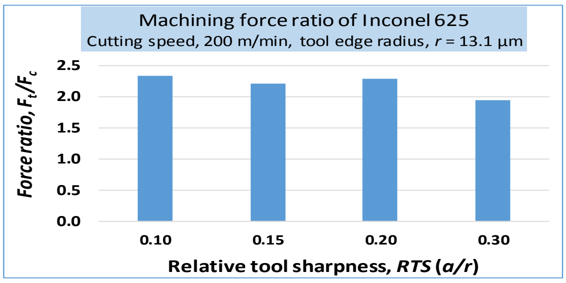

Figure 2. Thrust oriented micro cutting (Ft>Fc) with variation of *RTS*

As shown in Fig. 3, high quality finishing surface (R_a 69 nm) obtained with improvement of surface profile at *RTS* 0.15 than *RTS* 0.10 and *RTS* 0.20. Thus, the there is a 'narrow *RTS* zone' where the 'exceptional' surface finishing and surface profile improvement obtained for Inconel 625.

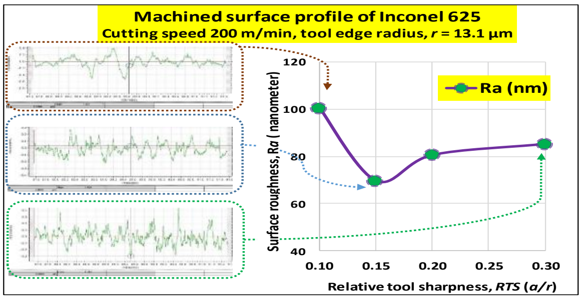

Figure 3. Surface finishing improvement with variation of *RTS*

3.1. Analysis for Ti6Al4V

Usually, continuous, flat, smooth, ribbon like chips produced during ultra-precision cutting of Ti alloy. However, SEM observation of chips at *RTS* < 0.10 shows distinct characteristics of perforated surface. Thus, complete solid chip is a significant characteristics for shearing mechanism at large *RTS* and incomplete perforated chip could be sign of dominant material deformation mechanism at much smaller *RTS* as shown in Fig. 4.

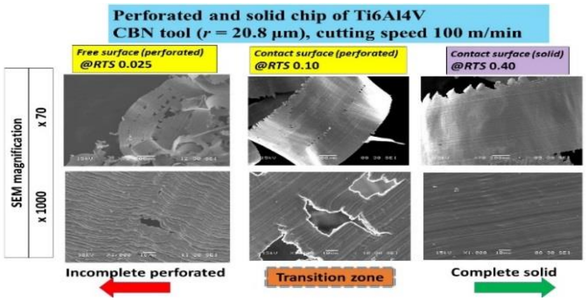

Figure 4. Ti alloy chip perforation behaviour with *RTS*

Tool edge radius plays a significant role on machined surface integrity as illustrated in Fig. 5. At larger *RTS* 0.4, shearing is the dominant cutting mechanism with existence of micro-cracks. By reducing *RTS* to 0.1, surface integrity seems improving with lesser number of micro-cracks due to change in cutting mechanism. At much smaller *RTS* 0.05, surface quality deteriorates with severe ploughing marks observed.

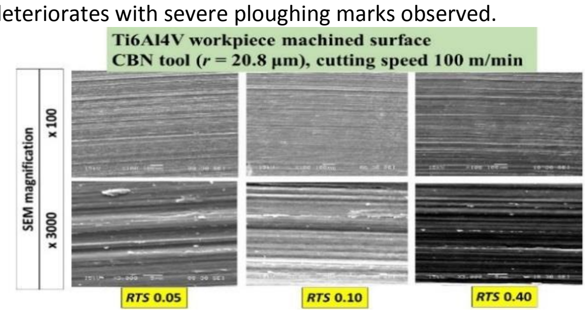

Figure 5. Variation of surface integrity of Ti alloy with variation of *RTS*

Relationship of nominal rake angle (γ) and instantaneous rake angle (γ_{ne}) can be given in terms of relative tool sharpness as:

$$\gamma_{ne} = \sin^{-1}(a/r - 1) = \sin^{-1}(RTS - 1) \qquad \text{-------- (2)}$$

Average flow stress (σ) obtained, with experimental data of cutting force (F_c),thrust force (F_t), undeformed chip thickness (a) and width of cut (w), from equation [6] where material flow angle (φ_{ne}) calculated with equation developed [7].

$$\sigma = \frac{(F_c sin\varphi_{ne} + F_t cos\varphi_{ne})\, sin\varphi_{ne}}{a * w} \qquad \text{-------- (3)}$$

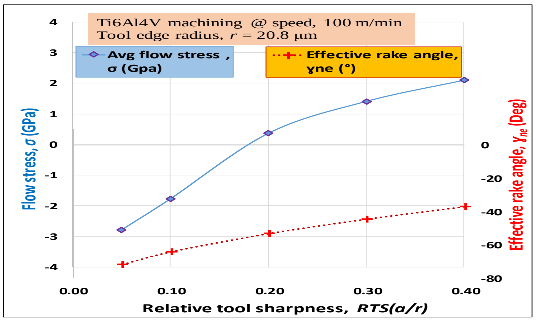

Figure 6. Variation of material flow stress with *RTS* for Ti alloy

As shown in Fig. 6, higher *RTS* of 0.4, flow stress is positive suggesting effective tensile stress similarly induced in conventional cutting mechanism even the effective rake angle is negative (-36.86°). Reducing *RTS* to smaller value 0.1, flow stress changes from tensile to compressive. By reducing *RTS* to much smaller value (0.05), Ti alloy exhibits highly compressive stress (σ = -2.8 GPa) where material ploughing could be dominant mechanics at highly negative effective rake angle (-71.77°).

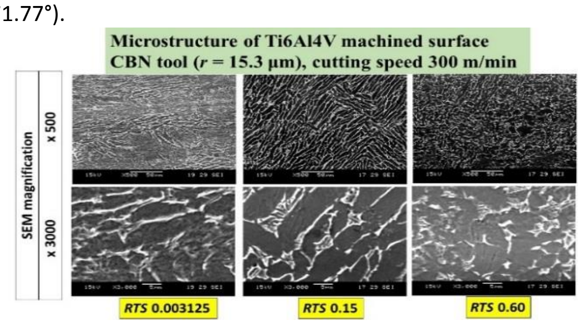

Figure 7. Variation of Ti6Al4V microstructure and grain with *RTS*

Fig. 7 shows variation of machined surface microstructure in SEM. At larger *RTS* of 0.6, with shearing dominant cutting mechanism, globular structure of grain noticed for both for α grain (black) and β inter granular (white). Reducing *RTS* to 0.1, both α and β grain become elongated. At extreme small *RTS* 0.003125, distortions of both α grain (black) and β inter granular (white) are noticed. Therefore, reducing *RTS* to extreme low value, material deformation transforms to rubbing with deteriorating surface quality and grain rubbing for Ti6Al4V.

4. Conclusions

- Edge radius effect is significant for surface integrity and *RTS* is dominant parameter of Ti6Al4V and Inconel 625 to achieve high quality finishing at *RTS* < 0.20.
- Perforated chip formation observed in transition zone (*RTS* <0.10) between complete and incomplete chip.
- Material flow stress changes from tensile to compressive at smaller *RTS* < 0.10, which is favourable for extrusion-like deformation mechanism.
- Reducing *RTS* to extreme lower value, material deformation transforms to rubbing mechanism as observed with Ti6Al4V grain distortion.
- Applicability of this novel study lies in its ability to machine superior surface without requiring secondary finishing process of difficult-to-cut materials.

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