Effect of machining parameters on cutting force and surface integrity when high-speed turning AD 730™ with PCBN tools

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Abstract

The novel wrought nickel-based superalloy, AD 730™, is a good candidate material for turbine disc applications at high temperatures beyond 650 °C. The present study focuses on the machining performance of this newly developed alloy under high-speed turning conditions with advanced PCBN tools. Meanwhile, the machined surface integrity as influenced by cutting speed and feed rate was also investigated. The surface integrity was thoroughly characterized in terms of surface roughness and morphology, machining-induced plastic deformation, white layer formation, and residual stresses. It has been found that the cutting speed and feed rate had a strong effect on the cutting forces and resultant surface integrity. The cutting forces required when machining the alloy were gradually reduced with increasing cutting speed, while at 250 m/min and above, the flank tool wear became stronger which led to increased thrust force and feed force. A higher feed rate, on the other hand, always resulted in higher cutting forces. Increasing the cutting speed and feed rate in general deteriorated the surface integrity. High cutting speeds within the range of 200–250 m/min and a low feed rate of 0.1 mm/rev are preferable in order to implement more cost-effective machining without largely reducing the surface quality achieved. The formation of tensile residual stresses on the machined AD 730™, however, could be of a concern where good fatigue resistance is critical.

Keywords Nickel-based superalloy · High-speed turning · Cutting forces · Surface integrity · AD 730™ · Cubic boron nitride (CBN) tool

1 Introduction

Increased demand for higher gas turbine efficiency has promoted the development of nickel-based superalloys in order to withstand higher operating temperatures. The strive for increased pressure ratio as well as reduced cooling air consumption leads to increased temperatures in the rim sections of high-pressure turbine discs for example. Development of advanced nickel-based superalloys for turbine discs with good properties above 700 °C and their applications in high-

efficiency gas turbines consequently become crucial for the global leading turbine manufacturers [1]. At such high temperatures, state-of-the-art disc alloys such as Inconel 718 cannot be used as the microstructure and mechanical properties will become unstable and start to degrade in a short time. AD 730™ is a novel nickel-based superalloy developed by Aubert & Duval [2]. The good workability of the alloy enables it to be delivered through the low-cost cast/wrought route. Moreover, Devaux et al. [3] performed a series of mechanical tests on AD 730™ from room temperature to elevated temperatures. The alloy exhibits an excellent combination of mechanical properties, high-temperature capability up to 750 °C owing to the γ/γ' microstructure, and material cost. It shows great potential for high-temperature disc applications and offers possibilities for improved turbine performance with enhanced energy conversion efficiency and better durability.

Thakur and Gangopadhyay [4] recently reviewed the studies regarding the issues of surface integrity induced when machining nickel-based superalloys. It is widely agreed that these alloys are difficult-to-cut materials regardless of the type of machining being used. The alloys can retain high

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mechanical strength to elevated temperatures, which requires high cutting forces during machining. Meanwhile, the heat generated at the tool/workpiece interface cannot be rapidly dissipated due to the low thermal conductivity. As a result, high cutting temperatures and sharp temperature gradients in the surface material are often created. The poor machinability gives rise to a high tendency of rapid tool wear and could also result in undesirable changes to surface integrity. Ulutan and Ozel [5] performed a study including a review of the surface integrity problems that are commonly created on machined nickel-based superalloys. White layer formation and generation of tensile residual stresses have been found to frequently take place on the machined surfaces, which are severe threats to fatigue properties. Using the acoustic emission technique, Guo and Schwach [6] found that in rolling contact fatigue the machined samples in which no white layer has been induced are more resistive to crack initiation and propagation and, therefore, showed a longer lifetime when compared to those samples with a white layer. The studies performed by Choi [7], on the other hand, demonstrated that residual stresses could influence the fatigue life of a machined component by more than 40%. This is primarily attributed to the residual stress field influencing the stress intensity at the crack tip, e.g., the stress intensity is increased if tensile residual stresses are present and incorporated. Schwach and Guo [8] investigated the effects of surface integrity, especially the residual stresses, on the fatigue resistance of the components machined by hard turning. The fatigue life was significantly prolonged for the samples in which surface and near-surface compression was produced. As for many other nickel-based superalloys, machining of AD 730™ can be a challenging process. Knowledge is needed of the machinability of the alloy under varied cutting conditions in order to develop the optimal solutions for different machining tasks. It is of a critical need to not only minimize the machining cost by increasing the machining efficiency and reducing the energy input and tool wear rate but also meet the high requirements on the surface quality/integrity for good fatigue properties. However, few relevant studies have been reported so far for this novel superalloy.

Turning operations comprise a large portion of the metal cutting processes in the turbomachinery industry. High-speed turning has been used to manufacture components where a high volume of material has to be removed. It can dramatically increase the productivity, thereby reducing the lead time and manufacturing cost. Plenty of studies have been carried out on high-speed turning in recent years. Great attention was paid on Inconel 718, with a particular interest of the tool wear mechanisms, cutting dynamics, machinability of the alloy, and surface integrity issues as influenced when using different machining parameters and cutting tools. Thakur et al. [9] machined the alloy Inconel 718 by high-speed turning, and they found that cutting speed and feed rate are two of the main cutting variables which strongly affect the machining

efficiency, cutting forces and corresponding energy consumption of the process, tool life and wear mechanisms, and final surface quality/integrity. Pawade et al. [10] conducted an investigation into the effect of tool cutting edge geometry and machining parameters, including cutting speed, feed rate, and depth of cut, on the cutting forces, surface roughness, and surface damages of high-speed turned Inconel 718 with PCBN inserts. It showed that all the cutting force components were reduced in magnitude with increasing cutting speed from 125 to 475 m/min. In addition, the higher cutting speeds produced lower values of surface roughness and less surface flaws. The feed rate also had a significant influence on the cutting forces; however, its effect on the surface roughness and surface damages was less dominant in comparison with that given by the cutting speed. Pawade et al. [11] further characterized the residual stresses and work hardening induced during the high-speed turning, and it was found that turning at the highest speed (475 m/min), lowest feed rate (0.05 mm/rev), low to medium depth of cut (0.5–0.75 mm), and with a honed cutting edge can introduce preferable compressive residual stresses on the machined surface and moderate working hardening in the sub-surface layers. Kishawy and Elbestawi [12] studied the tool wear and surface integrity when high-speed turning the hardened steel with PCBN tools. The findings also revealed the possibility of optimizing the cutting speed to generate favorable surface morphology and residual stresses. The experimental work performed by Lin [13] on the austenitic stainless steel once more highlighted the significant impact of cutting speed and feed rate on the developed surface integrity in high-speed turning despite the material to be machined. The results showed that a reduced feed rate led to lower surface roughness. However, a critical value was suggested since if the feed rate is smaller than 0.02 mm/rev, the surface roughness will be increased due to chatter phenomena. The increased cutting speed was found to deteriorate the surface roughness as the higher cutting temperature caused softening of the cutting tools.

The cutting speed limit in high-speed turning relies on the advances in cutting tool materials. When turning nickel-based superalloys with conventional cemented carbide (WC) tools, the cutting speeds are mostly limited in the range of 10–30 m/min. The introduction of coatings allows a higher cutting speed above 50 m/min; however, it can hardly exceed 100 m/min. Recent development of polycrystalline cubic boron nitride (PCBN) tools has led to a large extension of the cutting speed range to 200–300 m/min, or even up to 350 m/min. Costes et al. [14] and Zhou et al. [15] both performed a number of machining trials on Inconel 718 with PCBN tools, but with a different focus on the tool-life and wear mechanisms and the resultant surface integrity, respectively. It shows great potential to substantially increase the material removal rate and correspondingly benefit the production efficiency and cost by using the PCBN tools without largely compromising

the integrity and tolerance of the machined surface. This is because that the PCBN tools have lower abrasion and wear rate, higher hot hardness and strength, and better chemical resistance compared to the conventional carbide tools.

This paper presents a study in which the machinability of the nickel-based superalloy AD 730™ under high-speed turning conditions was assessed. A cylindrical bar was received and machined using uncoated PCBN tools. A wide range of cutting speed, from 150 to 300 m/min, and three different feed rates, from 0.1 to 0.2 mm/rev, were tested in order to investigate their effects on the cutting forces and surface integrity of machined workpiece. The surface integrity was thoroughly characterized in terms of surface roughness and morphology, machining-induced plastic deformation, white layer formation, and residual stresses using optical microscopy, scanning electron microscopy, and x-ray diffraction. The results of the study, for the first time, showed the performance of this newly developed superalloy in high-speed machining and also delivered a systematic evaluation of the surface integrity characteristics of machined AD 730™. In addition, the effect of the cutting speed and feed rate was also presented and discussed. These could be later used to guide the manufacturing processes for the high-temperature applications of the alloy in gas turbines or other industries.

2 Experimental work

A cylindrical bar of AD 730™ with a diameter of 75 mm and length of 500 mm was received from Aubert & Duval. The chemical composition of the bar material is given in Table 1. The heat treatment was conducted starting with a solution treatment at 1080 °C for 4 h /air cooling, followed by an isothermal aging at 730 °C for 8 h/air cooling in order to precipitate a high-volume fraction of the strengthening phase, γ' . This two-stage heat treatment resulted in a homogeneous microstructure with fine grains and the average grain size is in the range of ~10–15 μm , see Fig. 1. The 0.2% yield strength and ultimate strength of the aged alloy at room temperature is 1137 and 1547 MPa, respectively, according to the test results provided by the material supplier.

Uncoated PCBN inserts, SECOMAX™ CBN 170, were used in the new condition for all turning operations. The inserts are comprised of 65% CBN by volume (~2 μm grain size) and TiCN binder and reinforced by SiC whisker fibers, while the tool cutting edge was honed with an edge radius of 25 μm . Continuous longitudinal turning tests were conducted on the SMT500 CNC turning center, and the tool holder was PCLNL2525M12 JETL, which provides a negative rake angle and clearance angle of -6° . The coolant was applied with normal pressure at 8 bar. During the turning operations, the force signals were recorded by a Kistler 9257B force dynamometer. The test matrix included four cutting speeds, $V_c =$

Table 1 Chemical composition (percent of weight) of the aged AD 730™

Element	%wt
Ni	Bal.
Fe	3.91–3.96
Cr	15.53–15.57
Co	8.42
Mo	3.02
W	2.59
Al	2.31–2.32
Ti	3.51
Nb	1.12
B	0.01
C	0.01
Zr	0.034

150, 200, 250, and 300 m/min, three feed rates, $f = 0.1, 0.15$, and 0.2 mm/rev, and a constant depth of cut, $a_p = 0.25$ mm. For each test condition, a new insert was used, and the cutting length was set at 10 mm along the longitudinal direction. The used inserts were examined under the optical microscope, and it showed that generally they still maintained the good condition after the tests. The average tool flank wear was measured which is normally below 0.05 mm. However, considering that longitudinal turning was performed, tool wear is inevitably an influencing factor. Therefore, statistical characterizations and analyses of the cutting forces and machined surface integrity were carried out in the present study.

The surface integrity characterization was conducted close to the middle of the cutting length on all machined samples. Observation of the surface morphology was performed under a Hitachi SU-70 scanning electron microscope (SEM), which operates at 1.5–20 kV. The surface roughness was analyzed using an Alicona optical microscope with focus-variation, and the machined samples were then cross-sectioned along the cutting direction (CD), mounted, polished, and examined in the SEM. The deformed surface and sub-surface microstructure was characterized using both electron channeling contrast imaging (ECCI) and electron backscatter diffraction (EBSD) techniques. The residual stresses were measured by using x-ray diffraction on the machined surfaces in two in-plane directions, i.e., the CD and feed direction (FD). Cr- K_α was chosen for the residual stress measurements, and it gives a diffraction peak for the {220} family of lattice planes of the nickel-based γ matrix at $2\theta \sim 128^\circ$. In each measurement, the sample was tilted at nine ψ angles and the residual stress was calculated from the obtained diffraction peaks based on the classic “ $\sin^2 \psi$ ” method in the Noyan’s book [16] with an x-ray elastic constant of $5.22 \times 10^{-6} \text{ MPa}^{-1}$. Mukherji et al. [17] used high resolution x-ray and synchrotron diffraction to determine the lattice misfit between the γ' precipitates and γ matrix. The results suggested that small broadening can be

Fig. 1 Microstructure of the aged AD 730™ with a fine grain size. Insert showing the cuboidal γ' precipitates in the γ grains

expected from the diffraction peak of the γ matrix due to the presence of the fine and coherent γ' precipitates, but it does not necessarily influence the peak position significantly. Nevertheless, the present study only gives estimations of the macro-residual stresses induced in the surface layer. However, the micro-residual stresses within the γ and γ' phase are not separated as no peak deconvolution was conducted.

3 Results and discussion

3.1 Cutting forces

In a turning operation, the resultant force is comprised of three components, tangential cutting force, axial feed force, and radial thrust force. Figure 2 shows the variations of the three cutting force components when the cutting speed and feed rate was varied with a constant depth of cut, $a_p = 0.25$ mm. The cutting forces were continuously measured during the machining process. Stable values were received, and the average cutting forces were calculated and compared in Fig. 2 with small standard deviations, which are usually less than 2.5 N.

Generally, the cutting force stays at the highest in magnitude followed by the thrust force and then the feed force which is significantly smaller. As the cutting speed was increased, a continuous decrease of the cutting force took place, and this phenomenon was observed for all three feed rates, see Fig. 2a. An explanation is provided by the fact that the plastic work during machining generates large amounts of heat at the cutting zone. At higher cutting speeds, the time for heat dissipation into the surrounding materials becomes insufficient. Thus, the cutting temperature rises and leads to thermal softening of the workpiece being machined, which helps to remove the surface material with lower cutting force. In addition, Thakur et al. [18] found that the higher cutting speed increased the shear plane angle and reduced the chip-tool

contact area when turning the nickel-based superalloy. Larger shear plane angle, smaller chip-tool contact area, and higher shearing and chipping velocity are beneficial for reducing the cutting force and other force components [19]. It showed an agreement in the present study that the thrust force and feed force were also decreased at a higher cutting speed regardless of the feed rate applied; however, this only occurred in the low-speed range from 150 to 200 m/min, see Fig. 2b, c. The two force components started to increase when turning at 250 m/min and above.

Although within the cutting length generally no significant tool wear took place under the cutting conditions investigated, the increase of the cutting speed and feed rate still caused increased tool wear and had an influence on the tool wear mechanisms. Wider flank wear land is commonly measured during the same cutting time as an influence of the increased cutting velocity [20]. In the present study, flank wear, crater wear, and deformation of the cutting edge were found to become the dominant mechanisms for the wear of the cutting tools with increasing cutting speed. This is particularly the case when the cutting speed was increased to 250 m/min and above, see Fig. 3 for example. The reduced sharpness of the cutting edge due to the flank wear and deformation had unfavorable effects on the thrust force and feed force. The cutting force, on the other hand, was barely affected by these types of tool wear. It is in accordance with the findings reported by Wang et al. [21], which implies that the thrust force is the most sensitive force component to flank tool wear due to additional rubbing or plowing force on the tool-flank wear land.

The feed rate showed a relatively constant effect on the cutting forces, i.e., at all applied cutting speeds, increasing the feed rate caused an increase of the cutting force, thrust force, and feed force. The cutting force appears to be most sensitive to the increase of the feed rate since the largest increase was observed with its magnitude from 0.1 to 0.2 mm/rev. According to the study performed by Proskuriakov [22], an increased feed rate can also lead to temperature rise in the cutting zone when turning nickel-based superalloys using PCBN tools. However, unlike the effect of the cutting speed, it resulted in increased cutting forces. The investigation performed by Pawade et al. [10] in high-speed turning of Inconel 718 with PCBN tools also showed that in general higher cutting forces were required as higher feed rates were applied. The high feed rate contributes not only to a high volume of material removal but also to a high volume of and rate of material accumulation ahead of the cutting edge, which could generate significant compressive stresses on the cutting tool and workpiece material. Such effects were confirmed by Thakur et al. [18]. They found that the increase in feed rate gives rise to increased pressure on the cutting tool, and meanwhile it leads to higher magnitude of cutting force in high-speed turning.

Fig. 2 Effect of cutting speed and feed rate on the three cutting force components: **a** cutting force, **b** thrust force, and **c** feed force. Constant depth of cut at $a_p = 0.25$ mm

Machining of AD 730TM at a higher cutting speed and feed rate is preferable if taking the productivity and time efficiency into consideration. A relatively high cutting speed has also been found to benefit the machinability of the alloy in terms

Fig. 3 A SEM micrograph which demonstrates the dominant wear of the cutting tool after the turning operation at the cutting speed, $V_c = 300$ m/min, and with the feed rate at $f = 0.1$ mm/rev. Constant depth of cut at $a_p = 0.25$ mm

of reducing the cutting forces. A cutting speed in the range of 200–250 m/min appears to be advisable when turning AD 730TM with new PCBN tools since above 250 m/min rapid tool wear and large thrust force and feed force can be expected. Furthermore, it would be cost-effective if the turning is carried out with a low feed rate of 0.1 mm/rev since the higher feed rate requires higher cutting forces and correspondingly more energy input. Besides, a risk of cutting edge breakage and very short tool life was observed when the cutting tools were used at the large feed rate of 0.2 mm/rev because of the giant cutting forces.

3.2 Surface morphology

The machined samples exhibited good surface finish and low surface roughness with $R_a < 1.6$ μm , see Fig. 4. Increasing the cutting speed generally led to a tendency to reduced surface roughness, while the increase of the feed rate, on the contrary, consistently resulted in higher surface roughness values. Figure 5 shows the observations of the surface machined at the highest cutting speed, $V_c = 300$ m/min, and highest feed rate, $f = 0.2$ mm/rev. It consists of uniform well-defined feed marks even under the most aggressive cutting conditions, and chatter marks were not observed after turning. A close surface examination revealed the presence of micro-defects with several features. Surface cavities and cracked carbides are two types of defects that were often observed on the machined surfaces, as shown in Fig. 6a, b. The chemical composition in the cavity area is mostly comparable with that of the normal surface, which suggests that the cavities were mainly developed associated with the tool wear, e.g., a crack near the tool nose or the adhesion between the cutting tool and workpiece material.

Fig. 4 The achieved surface roughness varies as influenced by the cutting speed and feed rate applied

The authors [23, 24] previously have systematically characterized the surface integrity issues that might be created on the machined Inconel 718. Carbide cracking has been found to be one of the primary causes, which deteriorates the surface quality. The carbides tend to crack and break away from the surface. The carbide breakage leaves surface cavities, and some broken particles still remain inside. The smear and tear defects are formed when the detached carbide particles are re-deposited and dragged on the next pass from the surface. The carbide in AD 730™ also cracks when the material is being machined since it is brittle and unable to be deformed to the same extent as the plasticized surface and sub-surface layers. However, the carbide cracking, as shown in Fig. 6b, had less detrimental effects in terms of causing further dragging and tearing damages to the surface integrity.

With the progression of the turning, the developed built-up-edge (BUE) was separated and transferred from the tool/workpiece interface to the machined surface, and it induces surface defects of re-deposited debris, see Fig. 6c. These deposits coming from the BUE can subsequently give rise to dragging defects during the following pass of the cutting tool, see Fig. 6d. Material plastic flow and side flow were also observed as two typical types of surface defects on the machined samples, see Fig. 6e, f. The plastic flow often arises as a consequence of the high cutting temperature, giving rise to viscous surface materials, or due to the microstructural inhomogeneity, e.g., presence of an embedded secondary-phase particle beneath the surface. Kishawy and Elbestawi [25] performed experimental studies of hard turning in order to better understand the mechanisms behind the development of material side flow and investigate the effect of different process parameters. Under high cutting temperatures and pressure, the surface material can be severely deformed and pressed

Fig. 5 An overview of the surface machined with the highest cutting speed at $V_c = 300$ m/min and highest feed rate at $f = 0.2$ mm/rev. Constant depth of cut at $a_p = 0.25$ mm

aside. This effect will be stronger when notch wear occurs at the trailing edge.

Although the features observed in Fig. 6 were found on the machined surface regardless of the cutting conditions, there was a wide variation of the defect density, and the cutting speed appeared to have a dominant effect rather than the feed rate, particularly in the high-speed range. Strong surface plastic flow and side flow have been observed over the wide range of cutting parameters been tested, which implies that a high cutting temperature could be expected during the high-speed turning of AD 730™, even under relatively gentle and moderate cutting conditions. It has to be correlated with some intrinsic properties of the alloy, such as the high material strength and low thermal conductivity. The plastic flow became extremely considerable when turning at the highest speed of $V_c = 300$ m/min. Smearing of the surface material occurred in a large scale since the use of such a high cutting speed led to great heat generation and high cutting forces, which caused severe plastic deformation at the machined surface.

The observations on the machined surfaces also showed a high tendency to BUE formation when high-speed turning AD 730™, and it seems that a larger number of BUE deposits appeared as increasing the cutting speed. In the review paper by Thakur and Gangopadhyay [4], one can see that most of the previous studies showed opposite observations that a machined surface with better surface finish is normally formed using a higher cutting speed when machining nickel-based superalloys. It is primarily dictated by the lower cutting forces, less plastic deformation, and reduced tendency to BUE formation, which are associated with the increased cutting temperatures. The contradiction can be rationalized if the enhanced thermal impact at the higher cutting speed causes greater plastic deformation and exacerbates the adhesion

Fig. 6 Typical features of the observed surface micro-defects: **a** cavity, **b** cracked carbide, **c** BUE debris, **d** debris dragging, **e** plastic flow, and **f** side flow. All SEM micrographs were taken during the close examination on the machined surface corresponding to Fig. 5

between the cutting tool and workpiece material. In the present study, stronger surface plastic flow and greater crater wear have been observed as the cutting speed was increased. The surface roughness was influenced by two competing factors with increasing cutting speed. The increased number of BUE deposits has a detrimental effect on the surface roughness, while the greater plastic flow reduces the peak-to-valley height of the machined surface profile, and therefore, contributes to forming a relatively smooth surface.

Zhou et al. [23] performed high-speed turning on Inconel 718 with use of whisker-reinforced ceramic tools and systematically studied the machining-induced surface damages. It was found that the defects formed on the machined surface associated with BUE formation appear to be more noticeable when the alloy was machined at low feed rates. However, in this study, the deposition of BUE fragments to the machined surface was less predominant once the feed rate was decreased, and consequently, lower surface roughness values were measured. This can be attributed to the reduced cutting forces at the cutting tool edge, giving rise to less plastic deformation and work hardening at the tool/workpiece interface. The machining-induced plastic deformation as influenced by the cutting speed and feed rate will be presented and discussed in the next sections.

3.3 Plastic deformation

The turning operation caused great plastic deformation in the alloy with gradually reduced intensity from the machined surface, see Fig. 7. The grains, precipitates, and grain boundaries in the surface and near-surface regions have been heavily sheared and elongated towards the CD. Beneath the major deformation zone, the plastic deformation is characterized by slip activities, which leave a large number of deformed grains with slip bands in different slip planes. Eventually, the deformed microstructure runs out to the bulk material. Similar microstructural features were observed beneath the machined surface at all cutting speeds and feed rates. However, given by the qualitative assessment based on the SEM observations, the intensity of the plastic deformation induced by turning appeared to be increased at a higher cutting speed, if one compares Fig. 7a with Fig. 7c or Fig. 7b with Fig. 7d, as well as at a higher feed rate, by comparing Fig. 7a with Fig. 7b or Fig. 7c with Fig. 7d. Although the surface and sub-surface deformation is clearly viewed in Fig. 7, the accurate depth of the deformed layer could hardly be determined from the images. Therefore, it is difficult to make a comparison unless a significant difference exists between two cutting conditions.

EBS mapping provides an effective approach to quantitatively investigate the effect of cutting speed and feed rate on the machining-induced plastic deformation. An area, approximately 100 μm by 70 μm stretching from the surface been machined to the bulk material, was mapped with the resolution of 0.5 μm , and the intra-granular mis-orientation was automatically computed and stored. If the mis-orientation angle between two neighboring measured points falls in the range of 1° and 10° , it gives a low angle grain boundary (LAGB) in the map. Figure 8 shows the EBSD maps measured on the machined samples under varied cutting conditions corresponding to Fig. 7. It is evident that the amount of plastic strains is increased when approaching to the surface, which leads to stronger crystallographic rotation, and thereby to an increased number of LAGBs. Meanwhile, the LAGBs with a large mis-orientation angle between 5° and 10° (red lines) were found to emerge mostly in the surface and near-surface regions. The deformation gradient with the increased depth shows good agreement with the microstructural observations.

For each machined sample, three surface and subsurface areas with the same size as described above were mapped on the polished cross section in order to conduct statistical

analysis. The average LAGB frequency was plotted as a function of the depth by which the effect of cutting speed and feed rate was quantified, and the curves are presented in Figs. 9 and 10. At a given feed rate, increasing the cutting speed generally led to greater and deeper plastic deformation beneath the machined surface, see Fig. 9. However, it was clear that when the feed rate was kept constant at the low level of 0.1 mm/rev, no significant influence was identified of the cutting speed with regard to the depth of the deformed layer. In the low cutting speed range, even though the cutting forces were reduced with increasing speed, the turning operation still caused a larger amount and depth of plastic deformation on the machined surface. This indicates the coupling effects associated with the temperature rise as the cutting speed was increased, i.e., the stronger thermal softening contributes to less cutting forces, but the workpiece material is weakened in strength at higher temperatures which may allow greater plastic deformation to take place easily. Thus, as shown in the review paper by Ulutan and Ozel [5], the variation of surface and sub-surface deformation with cutting speed is not always consistent in machining, depending on the speed range and material to be machined.

Fig. 7 ECCI micrographs showing the machining-induced plastic deformation as influenced by cutting speed and feed rate. **a** $V_c = 150$ m/min and $f = 0.1$ mm/rev. **b** $V_c = 150$ m/min and $f = 0.2$ mm/rev. **c** $V_c =$

300 m/min and $f = 0.1$ mm/rev. **d** $V_c = 300$ m/min and $f = 0.2$ mm/rev. Constant depth of cut at $a_p = 0.25$ mm

Fig. 8 EBSD maps measured on the machined samples under varied cutting conditions corresponding to Fig. 7. Green lines represent low angle grain boundaries (LAGBs) with a mis-orientation angle falling in

the range of 1° and 5° between two neighboring indexes. Red lines represent those LAGBs with a mis-orientation angle falling in the range of 5° and 10°

When turning at 250 m/min and above, the effect of cutting speed became more predominant which is very likely due to the increased level of tool wear. The additional friction as the tool flank wears led to greater heat generation and plastic deformation. Young [26] directly measured the chip temperature during machining using an infrared radiation thermal tracer. The experimental data showed significant cutting temperature rise in relation to the increased level of tool wear. A high level of plastic deformation was induced in the case where the highest cutting speed of 300 m/min was applied. It has been long recognized that tool wear is one of the dominant causes, which lead to severe plastic deformation during machining. Ezugwu et al. [27] found that only slight plastic deformation was observed after 1 min turning of Inconel 718 at $V_c = 32\text{--}56$ m/min, $f = 0.13\text{--}0.25$ mm/rev, and $a_p = 1.2$ mm, while prolonged turning of 15 min turned out to cause considerable plastic deformation as the tool wears.

The enhanced mechanical loads when turning at a higher feed rate caused larger plastic deformation and increased deformation depth. Such an effect has been found for the entire range of cutting speed investigated in the present study, see Fig. 10, and is in accordance with that reported in the previous surface integrity studies on dry-milled titanium alloys, performed by Ginting and Nouari [28], and the nickel-based superalloy that has been machined with micro-drilling, conducted by Imran et al. [29].

3.4 Formation of white layer

White layer formation on a machined surface is mostly undesirable, especially for fatigue applications, since it could ease the initiation of fatigue cracks and their propagation at the early stage. Ulutan and Ozel [5] pointed out that severe plastic

Fig. 9 LAGB frequency plotted as a function of depth which quantifies the effect of cutting speed on the surface and sub-surface plastic deformation at a given feed rate: **a** $f = 0.1$ mm/rev, **b** $f = 0.15$ mm/rev, and **c** $f = 0.2$ mm/rev. Constant depth of cut at $a_p = 0.25$ mm

deformation, high cutting temperature, and flank wear rubbing can be considered to be the main causes of this layer. The observations on the cross-section of the machined samples confirmed that surface white layers were developed; however, a continuous white layer was only observed when turning

under the most abusive conditions, i.e., at the highest cutting speed of $V_c = 300$ m/min and feed rate of $f = 0.2$ mm/rev. The layer is very thin with a thickness of 1–2 μm, see Fig. 11a, and a close examination with ECCI revealed that it consists of nano-sized grains, see Fig. 11b. Adiabatic shear localization has been proposed to dominate the white layer formation during many machining processes of the nickel-based superalloys; it was suggested by Bushlya et al. [30] in high-speed turning of Inconel 718, Chen et al. [31] in broaching of Inconel 718, Veldhuis et al. [32] in turning of the powder metallurgical (P/M) nickel-based ME 16 superalloy, and Wusatowska-Samek et al. [33] in milling of the P/M alloy IN 100. The large plastic work and high strain rate combined with high cutting temperatures lead to localized shear deformation in the superficial layer. Grain refinement takes place in order to accommodate the considerable localized plastic strains.

Decreasing the cutting speed or feed rate cannot annihilate the white layer, but it can diminish the thickness and generate a discontinuous layer; an example is given in Fig. 12a where one can see that the white layer became irregular in thickness and indistinct in some regions with reducing the cutting speed to 250 m/min. Even though the risk for adiabatic shearing rises when materials are subjected to high strain-rate deformation, the cutting speed is not necessarily the sole factor that can trigger the white layer formation. A previous study conducted by the authors [31] has shown that a continuous white layer was developed in broaching even when the cutting speed was applied as low as at 3 m/min. This is attributed to the high levels of plastic work embedded on the surface material, while the consequent local temperature rise and sharp temperature gradient further aggravate the surface deformation. It has been found that the cutting forces are sensitive to the feed rate. The reduction in feed rate lowers the cutting forces, leading to less plastic deformation at the machined surface, and thereby, also contributes to the partial annihilation of the white layer, as shown in Fig. 12b.

Although in most samples a global white layer can hardly be observed, areas with white layer fragments are present within a few surface grains. It is not far-fetched to correlate the phenomenon with the variations of the cutting forces in turning, local microstructure inhomogeneity, and preferable grain orientations with regard to shear deformation. Despite falling out of the scope of the present study, it would be of great interest to ascertain these effects in the future work.

The microstructural characterization, presented in Sect. 3.3 and this section, clearly showed the possibility of reducing the plastic work during the high-speed turning of AD 730™ by using a lower cutting speed or feed rate. It can effectively retard the surface shear localization and introduce less plastic strains to the microstructure beneath the machined surface. The reduced plastic work when turning at the lower cutting speeds and feed rates, on the other hand, explains the decrease of the number of the defects associated with BUE formation on the machined surface, as described in Sect. 3.2.

Fig. 10 LAGB frequency plotted as a function of depth which quantifies the effect of feed rate on the surface and sub-surface plastic deformation at a given cutting speed: **a** $V_c = 150$ m/min, **b** $V_c = 200$ m/min, **c** $V_c = 250$ m/min, and **d** $V_c = 300$ m/min. Constant depth of cut at $a_p = 0.25$ mm

3.5 Residual stresses

Figure 13 presents a summary of the residual stresses and corresponding peak broadening, i.e., full width at half maximum (FWHM), measured at the machined surfaces using the

x-ray diffraction method with a beam size of 2 mm. The residual stress obtained, therefore, was a volume average over a large surface area on the machined sample, and the measurement uncertainty was indicated by the error bars. Overall, tensile residual stresses were developed, see Fig. 13a, b, and

Fig. 11 ECCI micrographs showing: **a** the formation of a continuous white layer on the surface machined with the highest cutting speed at $V_c = 300$ m/min, highest feed rate at $f = 0.2$ mm/rev, and constant depth

of cut at $a_p = 0.25$ mm, and **b** the nano-crystalline microstructure of the surface white layer. The regions where nano-sized grains can be observed are marked with dash lines in **b**

Fig. 12 An uneven and discontinuous surface white layer was formed when turning: **a** at a lower cutting speed ($V_c = 250$ m/min and $f = 0.2$ mm/rev), and **b** at a lower feed rate ($V_c = 300$ m/min and $f = 0.15$ mm/rev). Constant depth of cut at $a_p = 0.25$ mm

either increasing the cutting speed or feed rate generally led to higher surface tension, especially in FD. A similar effect has been found by Schlauer et al. [34] and Peng et al. [35] in the case of high-speed turning of Inconel 718. Arunachalam et al. [36] also observed a shift of the residual stress from compression to tension with increase of the cutting speed in another case of face turning. Sharman et al. [37] reported their findings on the residual stresses generated in Inconel 718, which has been machined by turning, while it showed apparent disagreement that the surface tensile residual stress started to decline as the cutting speed was increased. The increase of the feed rate, on the other hand, still turned out to give a slight increase of the surface tension. The diverse results demonstrate the complexity with regard to the residual stress formation in machining, which is influenced by material properties, tool parameters, and cutting conditions applied.

Residual stresses are developed on a machined surface since the machining produces non-uniform plastic deformation in the surface and sub-surface layers. Tensile residual stresses will be created if an overall compressive deformation has been induced during machining, and vice versa. Mechanical and thermal loads always exist simultaneously when machining an alloy. The mechanically induced residual stresses could be either compressive or tensile, which depends on the relative dominance of the compressive plastic deformation ahead of the cutting tool tip and the tensile plastic deformation behind it, arising from rubbing of the tool flank face, for example. The heat generated in the cutting zone, on the other hand, causes compressive deformation of the surface layer as the thermal expansion is constrained by the underlying materials. The thermally induced residual stresses, therefore, are always developed in tension and mostly isotropic in magnitude.

Given the significant difference of the surface residual stresses in the two measured directions, the mechanical work most likely dominated the residual stress development when turning at the low cutting speed, $V_c = 150$ m/min, and feed rate, $f = 0.1$ mm/rev, and it led to anisotropic plastic deformation of the surface material. The residual stress in CD is much

more tensile compared to that in FD. Nevertheless, with the specific cutting setups and tool geometry used in the current study, it was clear that the surface layer underwent great compressive deformation and consequently tensile residual stresses were developed. The deformation behavior can be modified by using a greater negative rake angle or larger honed radius, as suggested by Dahlman et al. [38] and Coelho et al. [39], which have been found to lead to additional plowing at the trailing edge, and thereby increase the compressive nature of the residual stresses induced by machining.

It was evident from the surface morphology and microstructural characterizations that the thermal impact on surface integrity was enhanced with increasing cutting speed. This explains the general tendency that greater surface tension was produced when turning at the higher cutting speeds. Comparable tensile residual stresses at a high level were measured in CD and FD on the samples machined at the highest cutting speed of 300 m/min, which indicates that the thermally induced residual stresses gradually became dominant on the machined surface. At the low feed rate of 0.1 mm/rev, the temperature rise at the surface during machining might not be considerable with increasing cutting speed. The effect of the cutting speed on the surface residual stress in CD exhibited less consistency, which is very likely attributed to the coupling effects of the decreased cutting force and increased cutting temperatures.

Turning at a higher feed rate resulted in a remarkable increase of the surface tension in FD as the increased pressure in FD caused enhanced compressive plastic deformation. In addition, a higher cutting temperature can be expected, as discussed in the previous sections, which also contributed to the overall higher tensile residual stresses at the machined surface. Larger surface tension was measured in FD, instead of in CD, on the samples machined at the higher feed rate of 0.15 and 0.2 mm/rev. With regard to the effect of feed rate on the residual stress in CD, when turning at the high-speed range of 250 to 300 m/min, it follows the general trend. However, at relatively low cutting speeds, the machined surface exhibited reduced tension

Fig. 13 Effect of cutting speed and feed rate on the surface residual stress in **a** the cutting direction (CD) and **b** the feed direction (FD). **c** The corresponding peak broadening, i.e., full width at half maximum (FWHM), when measured on the machined surfaces

in CD as the feed rate was slightly increased from 0.1 to 0.15 mm/rev. In the low-speed range, the higher feed rate was found to cause greater notch wear. The findings by Tian

et al. [40] in high-speed milling of Inconel 718 indicated that the notch at the cutting edge gives rise to a stronger plowing effect. The additional tensile deformation will facilitate the formation of compressive residual stresses. With the further increase of the feed rate to 0.2 mm/rev, the increased friction as the tool wear became stronger led to greater heat generation, enhanced the thermal impact, and thereby resulted in the high tension at the machined surface. It has been shown that the surface residual stresses were created with the combined influences arising from both mechanical and thermal plastic deformation, and the relative significance varies from one cutting condition to another. Nevertheless, it should be noted that the overall plastic deformation on the machined surface was increased with increasing cutting speed and feed rate, which can be indicated by the larger peak broadening, as shown in Fig. 13c, and it verifies the findings from the EBSD studies.

It was evident that increasing the cutting speed or feed rate has detrimental effects with respect to the surface integrity achieved. However, the surface quality is not significantly compromised with the slight increase of the cutting speed below 300 m/min, in particular at the low feed rate of 0.1 mm/rev. A deteriorated surface with substantial surface defects, severe plastic deformation, and high tensile residual stresses was obtained when turning at 300 m/min. Moreover, the reduced surface quality is not negligible as the feed rate is increased.

4 Conclusions

In the present work, the nickel-based superalloy AD 730™ is machined by high-speed turning using uncoated PCBN tools. The main conclusions are summarized in the following:

1. The cutting force is the highest force measured, followed by the thrust force, and the feed force is significantly smaller. Increasing the cutting speed reduces the cutting forces due to an increased cutting temperature. However, when the cutting speed exceeds 250 m/min, the flank wear becomes stronger and leads to increased thrust force and feed force. A higher feed rate, on the other hand, always results in higher cutting forces.
2. A machined surface with good surface finish ($R_a < 1.6 \mu\text{m}$) can be produced using the cutting setups and parameters tested in this study. Increasing the cutting speed generally leads to a tendency to reduced surface roughness, while the increase of the feed rate results in higher surface roughness values. The main types of surface defects observed on the machined surfaces include surface cavities, cracked carbides, BUE deposition and dragging, plastic flow, and side flow.
3. Larger and deeper plastic deformation are introduced beneath the machined surface with increasing cutting speed

and feed rate. Surface white layers are formed in the machined samples. However, only when turning under the most abusive conditions, a continuous white layer is developed at the machined surface.

4. Under the cutting conditions investigated, tensile residual stresses have been found to be created at the machined surface. Either increasing the cutting speed or feed rate generally results in higher surface tension.

Finally, a medium cutting speed in the range of 200–250 m/min and a low feed rate of 0.1 mm/rev is suggested when high-speed turning AD 730™ with PCBN tools, which produces a good combination of machining efficiency, energy consumption, and resultant surface integrity. The machined surface in general conforms to the specifications normally used for gas turbine components. However, the high tendency of forming tensile residual stresses on machined AD 730™ could be an issue that needs to be addressed for applications critical to fatigue.

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