The International Journal of Advanced Manufacturing Technology (2018) 96:2421–2430
https://doi.org/10.1007/s00170-018-1721-7

ORIGINAL ARTICLE

Effects of cutting parameters and tool nose radius on surface roughness and work hardening during dry turning Inconel 718

Yang Hua [1,2] · Zhanqiang Liu [1,2]

Received: 23 August 2017 / Accepted: 5 February 2018 / Published online: 22 February 2018

Abstract

The performance of a machined part is significantly influenced by its various surface integrity characteristics. However, the surface integrity of a machined part depends on the material and the cutting conditions employed. The present work investigates the effects of the cutting speed, the feed rate, and the tool nose radius on machined surface roughness, microhardness, and degree of work hardening of Inconel 718. Dry turning tests are performed using three different cutting speeds, three different feed rates, and two cutting tools with different nose radius. The results indicate that the feed rate and the tool nose radius have dominant effect on the machined surface roughness, whereas no clear tendency between the cutting speed and the surface roughness can be found. The results also indicate that the degree of work hardening is strengthened as the cutting speed and the feed rate increase. However, the degree of work hardening tends to be reduced significantly when larger tool nose radius is employed. Through the analysis of the results in the present work, the mechanism of the machined surface roughness and the degree of work hardening of dry turning Inconel 718 can be better understood. This can be contributed to investigate the effect of surface integrity on fatigue life of a machined part.

Keywords Inconel 718 · Surface roughness · Degree of work hardening · Cutting parameters · Tool nose radius

1 Introduction

Nickel-based superalloys have been extensively used in aerospace, chemical industry, marine equipment, and nuclear reactors due to their excellent properties such as high strength, oxidation and corrosion resistance, fatigue property, and fracture toughness at elevated temperatures [1]. Owing to the remarkable mechanical properties even at high temperature (600~800 °C), Inconel 718 is one of the most widely used nickel-based superalloys in critical components of aerospace engines and gas turbines [2].

Although Inconel 718 is the most commonly used nickel-based superalloy in aerospace industry, it faces considerable challenge during machining. This can be attributed to its low thermal conductivity, work hardening, and the presence of hard abrasive carbides on its microstructure-accelerating tool wear [3, 4]. Inconel 718 is thus classified as difficult-to-cut material.

The ever-increasing demands of precision, performance, reliability, and longevity of products require the surface quality of machined parts to satisfy more strict manufacturing standards. Performance of a machined part is significantly influenced by its various surface integrity characteristics. Studies have also shown the influence of surface roughness on the fatigue lifetime, especially when it comes to crack initiation [5]. However, surface roughness cannot alone evaluate the fatigue behavior of machined parts. Machining operations generate surface roughness but also work hardening in the surface layer. In the case of crack initiation on the machined surface, work hardening causes an improvement in the fatigue lifetime by delaying initiation of cracks [6]. These parameters can influence the fatigue lifetime. Therefore, the cutting parameters (such as the cutting speed, feed rate, depth of cut, lubrication, etc.) and the tool conditions (such as the tool geometry, tool material, coating, etc.) must be controlled and employed to achieve a favorable surface integrity.

Sharman et al. [7] carried out turning experiments of Inconel 718 to investigate surface integrity of machined parts.

✉ Zhanqiang Liu
melius@sdu.edu.cn

1 School of Mechanical Engineering, Shandong University, Jinan 250061, China

2 Key Laboratory of High Efficiency and Clean Mechanical Manufacture, Shandong University, Ministry of Education, Jinan, People's Republic of China

The feed rate was observed to be the main parameter influencing the surface roughness. It was found that the surface roughness tended to be higher as the feed rate increased. On the other hand, the cutting speed did not have significant effect on the machined surface roughness. Arunachalam et al. [8] investigated surface roughness when machining age-hardened Inconel 718. They concluded that the machined surface roughness was affected by the cutting speed. The machined surface roughness decreased obviously as the cutting speed increased from 150 to 375 m/min for fixed feed rate and depth of cut.

Pawade et al. [9] investigated the effect of machining parameters and cutting edge geometry on surface integrity of high-speed turning Inconel 718. It was obtained that the degree of work hardening beneath the subsurface was influenced by the tool cutting edge geometry and the depth of cut. However, the effect of cutting speed on the degree of work hardening was not obvious. Thakur et al. [10] carried out turning experiments of Inconel 718 to explore the effect of cutting parameters on the degree of work hardening. The results showed that the feed rate and cutting speed were the significant factors affect work hardening. The degree of work hardening was lower in the case of high cutting speed and feed rate ($V_c = 60$ m/min and $f = 0.2$ mm/rev, respectively) compared with the low cutting speed and feed rate ($V_c = 40$ m/min and $f = 0.08$ mm/rev, respectively). Coelho et al. [11] investigated the degree of work hardening on the machined surface and subsurface in turning Inconel 718. It was observed that an inverse relationship existed between the cutting speed and the degree of work hardening on the machined surface. The degree of work hardening reduced gradually with the increase of cutting speed.

Therefore, there is a certain lack of agreement in the literature regarding the tendency of surface roughness and degree of work hardening with cutting parameters. In addition, the effect of tool geometry such as tool nose radius on surface integrity, in particular on degree of work hardening, has been very limitedly researched, in spite of its significance. The tool geometry affects the degree of work hardening of the machined parts, due to that mechanical and thermal loads are modified by changes in the tool characteristics. This is why in the present work, the effect of tool nose radius on the surface integrity of machined surface in Inconel 718 will be studied.

The present work aims to focus on the investigation of the machined surface roughness and degree of work hardening during dry turning Inconel 718. It is one part of a general study on the effect of machining on the fatigue life of Inconel 718 aerospace engine parts. The general study consists of two stages involving firstly the effect of machining on surface integrity and secondly the effect of surface integrity on fatigue life. The present work investigates the first stage.

2 Experiments

The workpiece material employed in the present work was Inconel 718 which was solution treated and aged to a nominal bulk hardness of 375 ± 10 $HV_{0.05}$, and the initial sample was a cylindrical bar with a diameter 24 mm and a length 120 mm. The chemical compositions of Inconel 718 are shown in Table 1.

A set of experiments were carried out to investigate the effect of cutting parameters and tool nose radius on surface integrity of machined workpiece. All turning tests were conducted on a CNC turning center with a maximum spindle speed of 6000 rpm and a power rating of 28.66 KW. The cutting conditions employed in the turning tests are presented in Table 2. The carbide inserts ISO VBMT110304-1125 and VBMT110308-1125 with PVD coating (TiAlN) and a tool holder ISO SVJBR 2525M 11 were employed for turning Inconel 718. In order to avoid undesirable errors in machining tests, some preparations were performed. Before conducting machining tests, to remove out of roundness produced due to the previous operations, a thin layer (2 mm) from each sample was removed by machining. It has been shown that tool wear affected significantly the surface integrity such as surface roughness and work hardening [12]; therefore, each turning experiment was conducted using fresh tools to eliminate the influence of tool wear on surface roughness and degree of work hardening in the present work.

Surface roughness of the machined workpiece was measured with the help of a 3D-zoom surface measurement instrument VK–X250K. The machined workpiece was sectioned through wire electro-discharge machining, hot mounted in bakelite, ground using SiC paper, and polished with diamond grits. The microhardness on machined surface and subsurface was measured by means of the instrument HVS-1000, at a load of 50 g for 8 s, as shown in Fig. 1. Five points at the same depth were measured to ensure accuracy of measurement results.

3 Results and discussion

The present investigation dealt with the effect of cutting parameters and tool nose radius on several aspects of surface integrity such as surface roughness, microhardness, and the degree of work hardening of machined parts during dry turning of Inconel 718.

Table 1 Chemical compositions of Inconel 718

Element	Ni	Cr	Fe	Nb	Mo	Ti	Al	S
Wt%	52.88	19.00	18.33	5.18	3.00	1.00	0.52	0.09

Table 2 Cutting conditions in turning Inconel 718

Parameters	Cutting speed V_c (m/min)	Feed rate f (mm/rev)	Nose radius r (mm)	Depth of cut a_p (mm)
Levels	80, 100, 120	0.05, 0.15, 0.25	0.4, 0.8	0.4

3.1 Surface roughness

Among the surface topological parameters, surface roughness is considered as one of the main characteristics of machined surfaces. It greatly affects the wear resistance of the surfaces of the machined part, fatigue life, and ultimately the reliable function of the product during service. In the turning process, surface roughness is associated with the cutting parameters and the geometry of the cutting tool.

3.1.1 Effect of feed rate and cutting speed on machined surface roughness

As can be seen in Fig. 2, surface roughness increased with the increase of feed rate at various cutting conditions. In particular, when the feed rate increased from 0.15 to 0.25 mm/rev, its effect on surface roughness was more pronounced than when the feed rate increased from 0.05 to 0.15 mm/rev. It was evident (see Fig. 2a) that when feed rate increased from 0.05 to 0.25 mm/rev, surface roughness increased significantly from 0.42 to 5.51 μm when the cutting speed and tool nose radius were at the level of 120 m/min and 0.4 mm, respectively.

The relationship between the feed rate and surface roughness could also be illustrated by the residual height of feed marks. As can be seen from Fig. 3, the residual height of feed marks was more distinct when the higher feed rate was employed. As the feed rate increased from 0.05 to 0.25 mm/rev, the maximum residual height of feed marks increased dramatically from 3.12 to 16.03 μm when a smaller tool nose radius was utilized. The maximum residual height of feed marks also increased greatly from 3.03 to 10.16 μm with the increase of feed rate when the tool nose radius was at the level of 0.8 mm. As the feed rate increased, there was an increase in the cutting load on the cutting edge [13]. Therefore, more plastic deformation was formed and resulted in a higher surface roughness.

There was a slight decrease in surface roughness when the cutting speed increased from 80 to 120 m/min at the lower feed rate conditions (see in Fig. 2). On the other hand, the surface roughness tended to be increased with the increasing of cutting speed at the higher feed rate conditions. Therefore, it seemed that the relationship between the cutting speed and surface roughness could not be concluded.

Umbrello [14] affirmed that surface roughness diminished when the cutting speed increased from 50 to 70 m/min at various feed rates during dry machining Inconel 718. The similar trend was obtained by Zhou et al. [15] and Devillez et al. [16]. Nevertheless, Thakuret al. [17] stated that there was an increase in surface roughness when the cutting speed was raised from 51 to 124 m/min during machining Inconel 825.

In this work, surface roughness tended to be higher with the increase of cutting speed for a fixed feed rate of 0.25 mm/rev. This could be attributed to the tool wear according to Ezilarasan et al. [13]. The temperature increased at the contact area between the tool and workpiece as the cutting speed increased. Owing to the low conductivity of Inconel 718, the most of generated heat diffused into the tool. This induced tool wear and generated higher surface roughness. However, when the lower feed rate was utilized, the surface roughness decreased with the increase of cutting speed. This could be explained by the reduction in built-up edge [2].

In view of the results of the present work, no evident tendency between the cutting speed and surface roughness could be found. It indicated that the cutting speed was not the dominate factor for affecting surface roughness within the cutting conditions investigated.

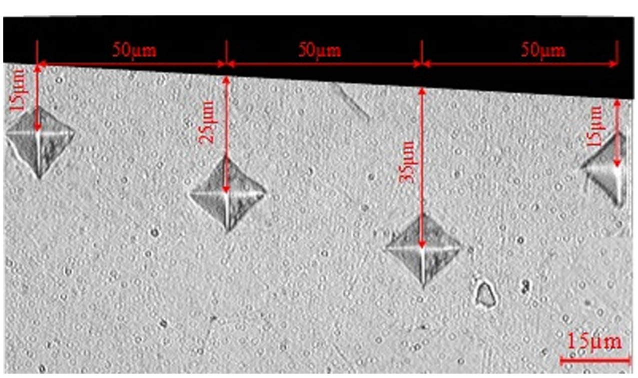


Fig. 1 The schematic diagram of microhardness measurement

3.1.2 Effects of the tool nose radius on machined surface roughness

Figure 4 illustrated the relationship between the tool nose radius and surface roughness. As can be seen in Fig. 4, the tool nose radius had a significant effect on surface roughness. The surface roughness was higher when the smaller tool nose radius was utilized. It was noted from Fig. 4a that an increase in tool nose radius led to the surface roughness diminishing greatly from 4.94 to 1.94 μm (diminishing 60.73%) with respect to the cutting speed and the feed rate was 80 m/min and 0.25 mm/rev, respectively.

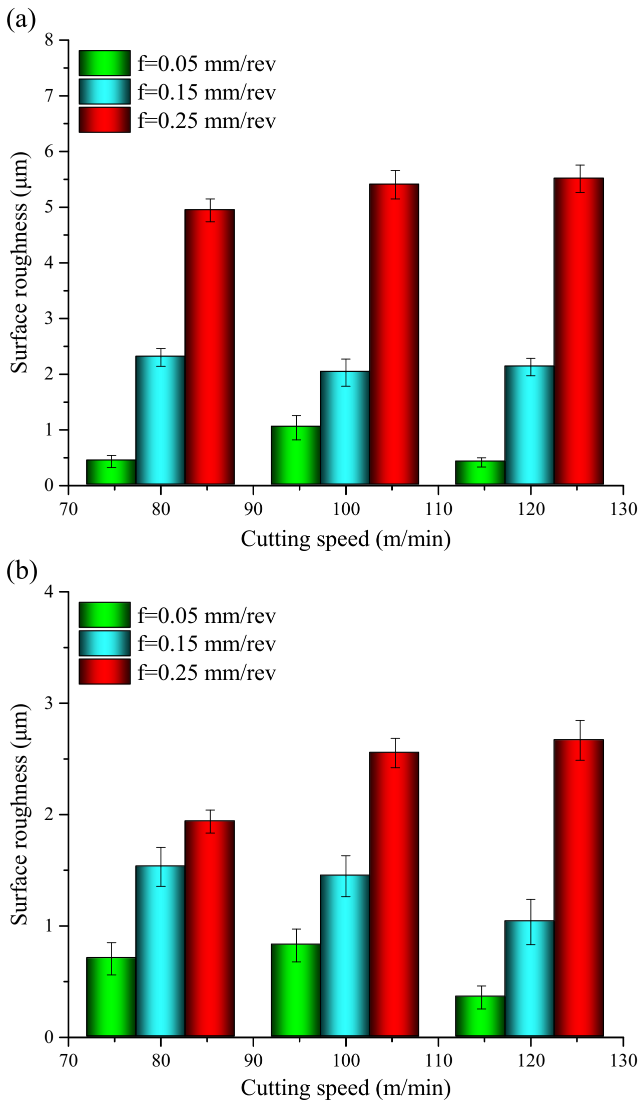


Fig. 2 Effect of feed rate and cutting speed on surface roughness at **a** r = 0.4 mm and **b** r = 0.8 mm

This trend was consistent with the research of Arunachalam et al. [6] who suggested that the larger tool nose radius induced the lower surface roughness. This could be explained that an increase in the tool nose radius resulted in an increment in contact length, and thus, the cusp height was reduced. The same trend was obtained by Nalbant et al. [18] who found that larger nose radius was the best adaptable parameter in terms of reducing surface roughness. However, Dufrenoy et al. [19] proposed that it was hard to establish a correlation between the evolution of nose radius and surface roughness.

In the present work, the surface roughness decreased with the increase of tool nose radius. When the larger tool nose radius was employed, the contact length between the tool and workpiece increased, as shown in Fig. 5. Hence, the residual height of feed marks was diminished and the surface roughness became lower. In addition, an increase in tool nose radius would enlarge the contact area between the chip and rake face, which induced higher resistance to scrape the machined workpiece surface. Therefore, the larger tool nose radius produced lower surface roughness. Figure 3 demonstrated that the residual height of feed marks caused by the larger tool nose radius was lower than that caused by the smaller one.

3.2 Microhardness depth profile of machined surface and subsurface

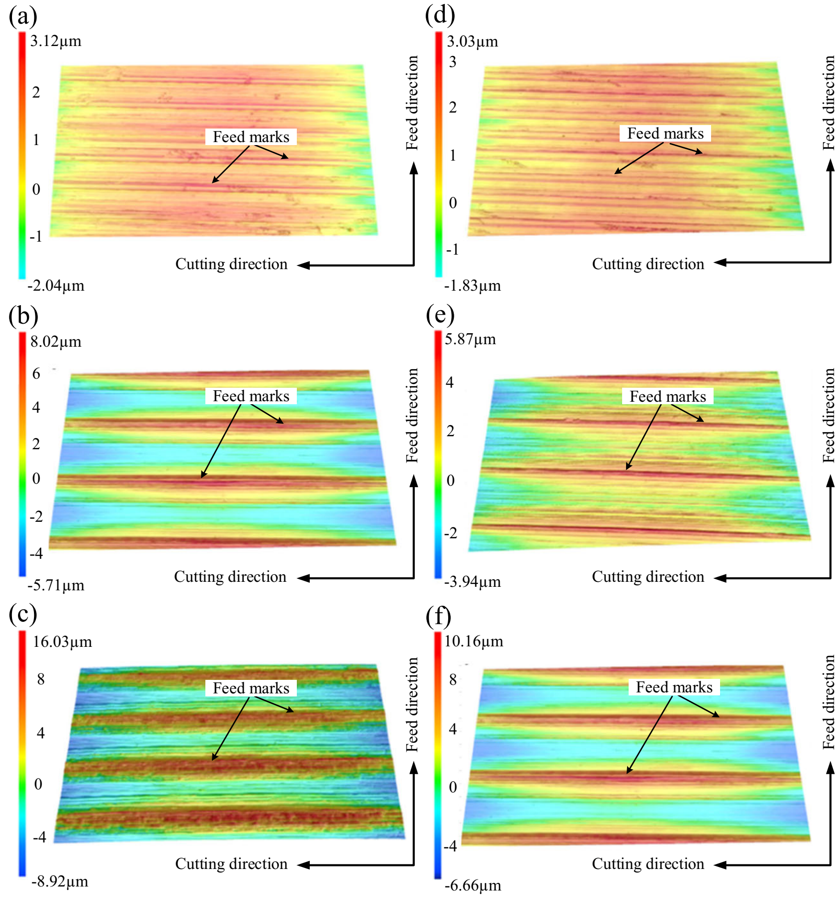
Microhardness of machined surface was influenced primarily by cutting parameters and tool geometry. The present research investigated the influence of the cutting speed, the feed rate, and the tool nose radius on the microhardness of machined surface and subsurface. Measurement of microhardness was carried out at different locations beneath the machined surface. Figure 6 shows the typical microhardness profiles of the machined subsurface, which illustrated the variation of microhardness with distance from the machined surface towards the bulk material under different cutting conditions.

It can be evidently seen from Fig. 6 that a steep microhardness gradient existed in the region between the depths of 15 and 55 μm beneath the machined surface. Microhardness was higher near the machined surface layer and which decreased gradually as the depth increased and finally approached to the average of bulk material microhardness 375 ± 10 $HV_{0.05}$ at a depth of about 55 μm beneath the machined surface. The microhardness near the machined surface was found approximately 1.09 to 1.2 times of the bulk material microhardness. The similar variation trend of microhardness was also observed by other authors [9, 16, 20].

The higher microhardness of the machined subsurface could be attributed to the accumulation of the dislocation density due to increased plastic deformation during machining. Particularly, in the case of the nickel-based alloy Inconel 718, its higher percentage element of Cr and Fe strengthened the grain boundaries with some metallic carbides (such as NbC and TiC) which impeded the movement of dislocation. The dislocation density increased and thus generated the amount of energy stored in dislocation, which resulted in the plastic deformation of materials more and more difficult [16]. Therefore, the microhardness of the machined subsurface became higher. Furthermore, Inconel 718 contained γ' ($Ni_3(Al,Ti)$) and γ'' (Ni_3Nb) precipitates, the main strengthening phases in the solution-treated condition of Inconel 718. Hence, the shear deformation during the chip formation of the Inconel 718 became difficult, which ultimately led to work hardening effect.

The microhardness of all the specimens varied between 398 and 452 $HV_{0.05}$ at the depth of 15 μm in this research. It was noticed that the microhardness near the machined surface layer reached the maximum value, and the depth of work hardening was almost up to about 75 μm beneath the

Fig. 3 3D surface morphology at cutting speed of 120 m/min. **a** f = 0.05 mm/rev, r = 0.4 mm. **b** f = 0.15 mm/rev, r = 0.4 mm. **c** f = 0.25 mm/rev, r = 0.4 mm, **d** f = 0.05 mm/rev, r = 0.8 mm. **e** f = 0.15 mm/rev, r = 0.4 mm. **f** f = 0.25 mm/rev, r = 0.8 mm



machined surface when the cutting speed was 120 m/min, the feed rate 0.25 mm/rev, and the tool nose radius 0.4 mm (see Fig. 6c). The lowest microhardness near the machined surface layer was obtained when turning at lower cutting parameters and larger radius, and the depth of work hardening was about 45 μm as shown in Fig. 6a.

Pawade et al. [9] concluded from machining experiments that the depth of work hardening was claimed to decrease with the increasing of cutting speed and depth of cut during turning Inconel 718, whereas the depth of work hardening tended to be increased when the higher feed rate was employed. According to Umbrello et al. [14], however, the depth of work hardening was found to increase with increasing cutting speed and feed rate. Ezilarasan et al. [13] demonstrated that the decrease in depth of work hardening with the increasing of cutting speed was not observed when Nimonic C–263 superalloy was machined by using whisker-reinforced ceramic inserts.

There did not appear to be significant difference in the depth of work hardening at various cutting speeds in this research (see in Fig. 6). This could be attributed to that the thermal softening was balanced by the strain rate hardening within the range of cutting conditions investigated. On the other hand, it was observed from Fig. 6 that the depth of work hardening increased when the feed rate increased from 0.05 to 0.25 mm/rev. As can be seen from Fig. 6b, for a fixed tool nose radius of 0.4 mm, the depth of work hardening was about 55, 65, and 75 μm at feed rates of 0.05, 0.15, and 0.25 mm/rev, respectively. This can be explained by that the higher feed rate generated higher cutting force which induced more severe plastic deformation; therefore, the depth of work hardening increased [13].

It was also observed from Fig. 6 that the deeper depth of work hardening was obtained at smaller tool nose radius, especially at a higher level of cutting speed and feed rate as shown in Fig. 6b, c. This disagreed with Madariaga et al. [21], who stated that deeper work hardening layer (100 μm) was obtained with large nose radius (4 mm). Although no specific explanation was provided by Madariaga, it was possible to speculate that the increased plowing force due to larger tool nose radius might be responsible for the depth of work hardening. However, in fact, the results of the present work showed that smaller tool nose radius induced deeper depth of work hardening. This will be discussed in more detail in the next section in this paper.

3.3 Degree of work hardening

Owing to the machined surface will be subject to the external conditions during service, the degree of work hardening on the

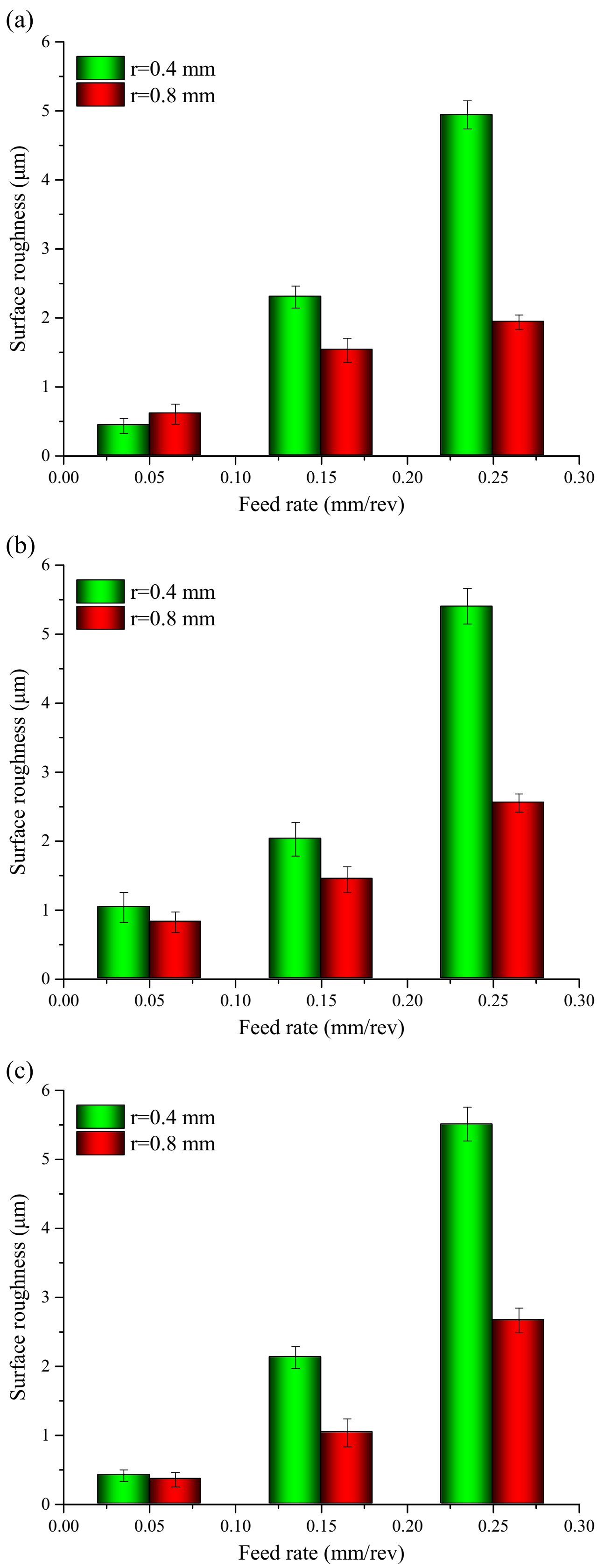


Fig. 4 Effects of tool nose radius on surface roughness at different cutting speeds. **a** $Vc = 80$ m/min. **b** $Vc = 100$ m/min. **c** $Vc = 120$ m/min

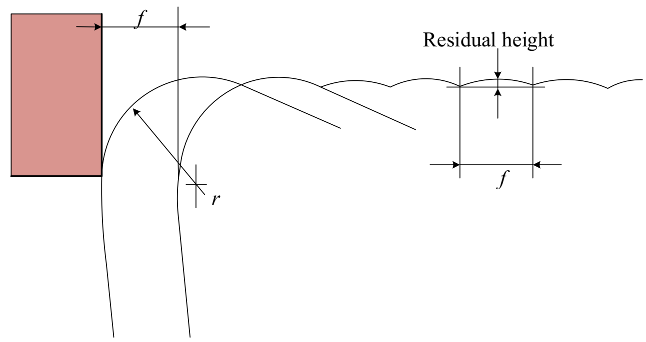


Fig. 5 Effects of tool nose radius on the residual height of feed marks

machined surface is critical. The degree of work hardening represented work hardening behavior of the work material as given by Eq. (1) which was used as a quantitative measure of integrity of the machined surfaces and subsurface. The

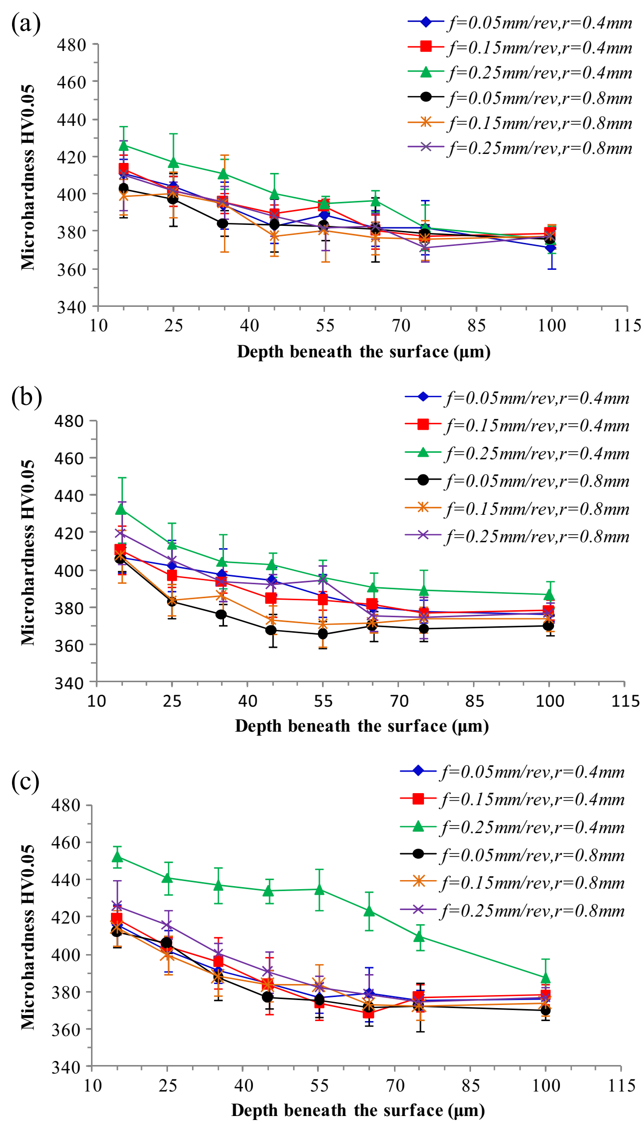


Fig. 6 Microhardness variations beneath machined surface at **a** $Vc =$ 80 m/min, **b** $Vc = 100$ m/min, and **c** $Vc = 120$ m/min

relationship between microhardness and fatigue crack propagation threshold value could be shown as Eq. (2) [22]:

$$\text{Degree of work hardening} = \frac{MH_s - MH_b}{MH_b} \times 100\% \qquad (1)$$

where MH_s and MH_b were microhardness for machined surface and bulk material, respectively.

$$\Delta K_{th} = C_1 (H_v + C_2) \left(\sqrt{area}\right)^{1/3} \qquad (2)$$

where ΔK_{th} was fatigue crack propagation threshold value, H_v was Vikers hardness, C_1 and C_2 were material independent constants, and $\sqrt{area}$ was representative geometrical parameter for defects or cracks.

Due to the size of the indenter which confined the distance between the measured point and the machined surface, it was hard to obtain the microhardness of the machined surface. The present work investigated the effect of cutting parameters and tool nose radius on the degree of work hardening at the depth of 15 μm beneath the machined surface.

3.3.1 Effects of cutting speed on degree of work hardening

The degree of work hardening at the depth of 15 μm beneath the machined surface was calculated by Eq. (1) for each of cutting conditions. Figure 7 shows the relationship between the cutting speed and the degree of work hardening. It was observed from Fig. 7 that there was an increment in degree of work hardening as the cutting speed increased from 80 to 120 m/min. The degree of work hardening increased dramatically from 13.53 to 20.59% (increasing 52.18%) with the increase of cutting speed (see Fig. 7a) for a fixed feed rate of 0.25 mm/rev. Thus, it was clear that the highest level of cutting speed induced the most amount of degree of work hardening on the machined subsurface.

Thakur et al. [10] found that the degree of work hardening was observed to be less in the case of high cutting speed (Vc = 60 m/min) compared with low speed (Vc = 40 m/min) when turning Inconel 718. This phenomenon was explained as that the high cutting speed induced high temperature which would result in thermal relaxation to reduce material strain hardening capacity. However, such relaxation and decrease in degree of work hardening was not seen while machining the nimonic C–263 alloy according to the research of Ezilarasan et al. [13]. The similar trend was obtained by Umbrello [14], who affirmed that the degree of work hardening increased when the cutting speed increased from 50 to 70 m/min in dry turning Inconel 718. But, both of the researches did not provide an explanation for this phenomenon.

An increase in the cutting speed indicated an increase in cutting temperature for cutting speeds between 75 and 200 m/min according to the research of Outeiro et al. [23], which implied that the degree of work hardening would be weakened

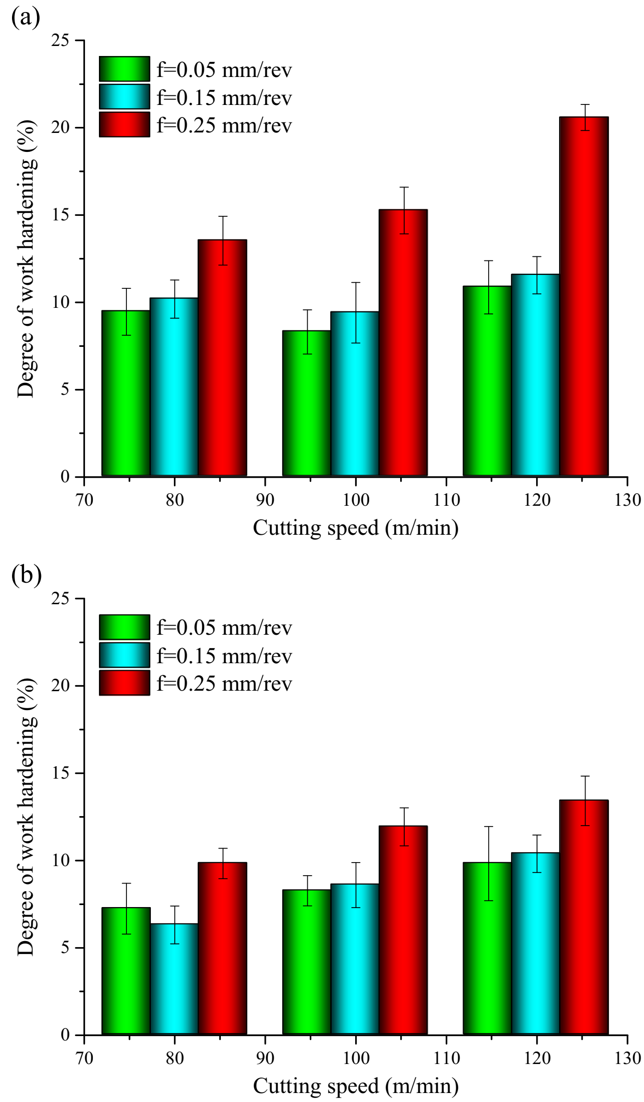


Fig. 7 Effects of cutting speed on degree of work hardening at **a** r = 0.4 mm and **b** r = 0.8 mm

by the increased cutting temperature. On the other hand, as Navas et al. mentioned in an article [24], the heat penetration diminished when the cutting speed increased. This was attributed to the fact that the contact time between tool flank face and workpiece surface was shortened as the cutting speed increased, which indicated that the degree of work hardening would be strengthened.

Yang et al. [25] demonstrated that the increase in the cutting speed inevitably resulted in the increase in strain rate, which led to higher yield strength of material. Hence, the effect of cutting speed on degree of work hardening was a complex interaction of thermal effect and mechanical effect during machining. In the present work, the tendency of degree of work hardening increasing with the increase of cutting speed suggested that the mechanical effect predominated in the interaction among the processing parameters investigated in this paper. According to Eq. (2), fatigue crack propagation threshold ΔK_{th} tended to be higher with the increase of microhardness, which suggested that fatigue crack initiation life would be prolonged during service. Consequently, combining Eqs. (1) and (2), it could be concluded that higher cutting speed induced greater degree of work hardening and improved fatigue crack propagation threshold. This was contributed to prevent fatigue crack propagating earlier during service.

3.3.2 Effects of feed rate on degree of work hardening

The relationship of feed rate and degree of work hardening is shown in Fig. 8. It was observed that the degree of work hardening tended to be higher when a higher feed rate was utilized. The trend was similar as that with the increase of cutting speed but induced a much greater slop than that with the cutting speed especially when the feed rate increased from 0.15 to 0.25 mm/rev. The degree of work hardening increased significantly from 10.87 to 20.59% (increasing 89.42%) with the feed rate increased from 0.05 to 0.25 mm/rev as shown in Fig. 8a. Thus, it can be concluded that the influence of feed rate on degree of work hardening was much greater than that of cutting speed at the same tool nose radius.

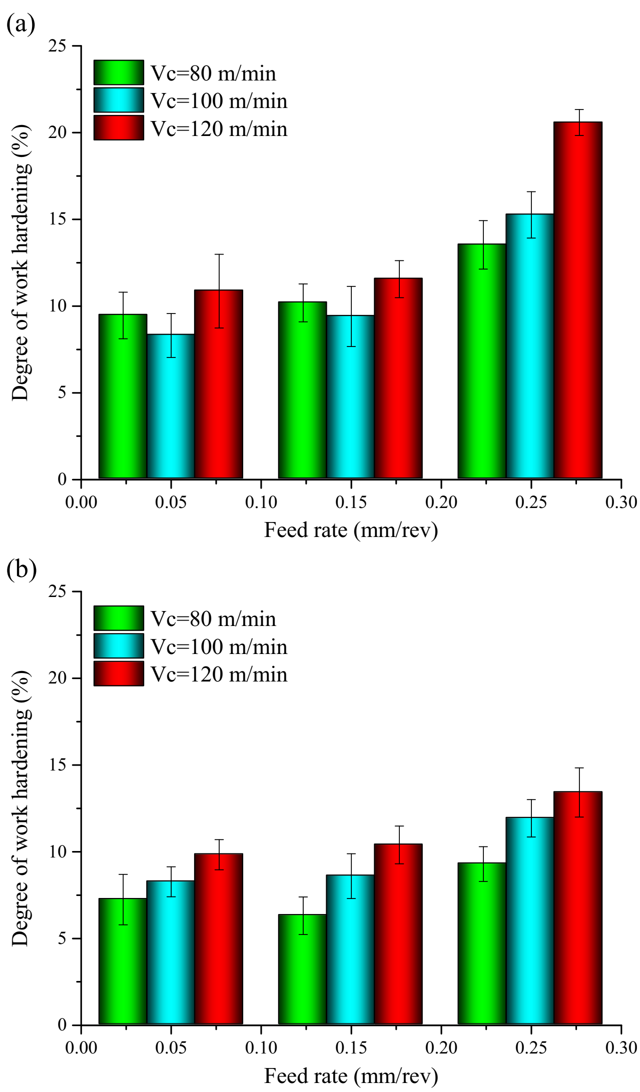


Fig. 8 Effects of feed rate on degree of work hardening at **a** $r = 0.4$ mm and **b** $r = 0.8$ mm

Thakur et al. [10] observed an inverse relationship between the feed rate and degree of work hardening during machining Inconel 718. The degree of work hardening was observed to be reduced at the higher feed rate of 0.2 mm/rev compared with the lower feed rate of 0.08 mm/rev. This would be attributed to an increase in cutting temperature which was due to the increased feed rate. Consequently, the material strain hardening effect reduced due to the higher temperature. On the other hand, such thermal softening behaviors was not observed by Umbrello [14] and Ezilarasan et al. [13], who found that the degree of work hardening increased as the feed rate increased. This could be illustrated that at a higher feed rate, the load on the cutting edge increased, thus inducing higher deformation and degree of work hardening.

An increase in feed rate generated higher cutting force, which indicated more severe plastic deformation. And it also increased the compressive zone in the region below the cutting edge, hence, strengthening the degree of work hardening. Meanwhile, the temperature increased due to that the feed rate increased according to the research of Outeiro et al. [23], which implied greater heat generation was associated with the plastic deformation of the material to form the chip. The heat generated in the cutting process led to the thermal softening that would reduce the degree of work hardening. However, that is not the case. Therefore, the effect of feed rate on degree of work hardening was a complex interaction of mechanical effect and thermal effect. In the present work, the results indicated that mechanical effect was the dominant factor in the generation of work hardening, according to the relationship between the degree of work hardening and fatigue crack propagation threshold value ΔK_{th} as shown in Eqs. (1) and (2). The increased feed rate generated the increased degree of work hardening giving rise to higher ΔK_{th}, which was beneficial to suppress fatigue crack initiation during service.

3.3.3 Effects of tool nose radius on degree of work hardening

Figure 9 shows the relationship between tool nose radius and degree of work hardening at various cutting conditions. It was observed that the degree of work hardening at tool nose radius 0.4 mm was greater than that at tool nose radius 0.8 mm. It can be seen from Fig. 9c that the degree of work hardening increased remarkably from 13.42 to 20.59% (increasing 53.43%) with the tool nose radius decreased from 0.8 to 0.4 mm for the fixed cutting speed of 120 m/min and feed rate of 0.25 mm/rev. This agreed well with Sasahara et al. [26] who demonstrated that the degree of work hardening on the

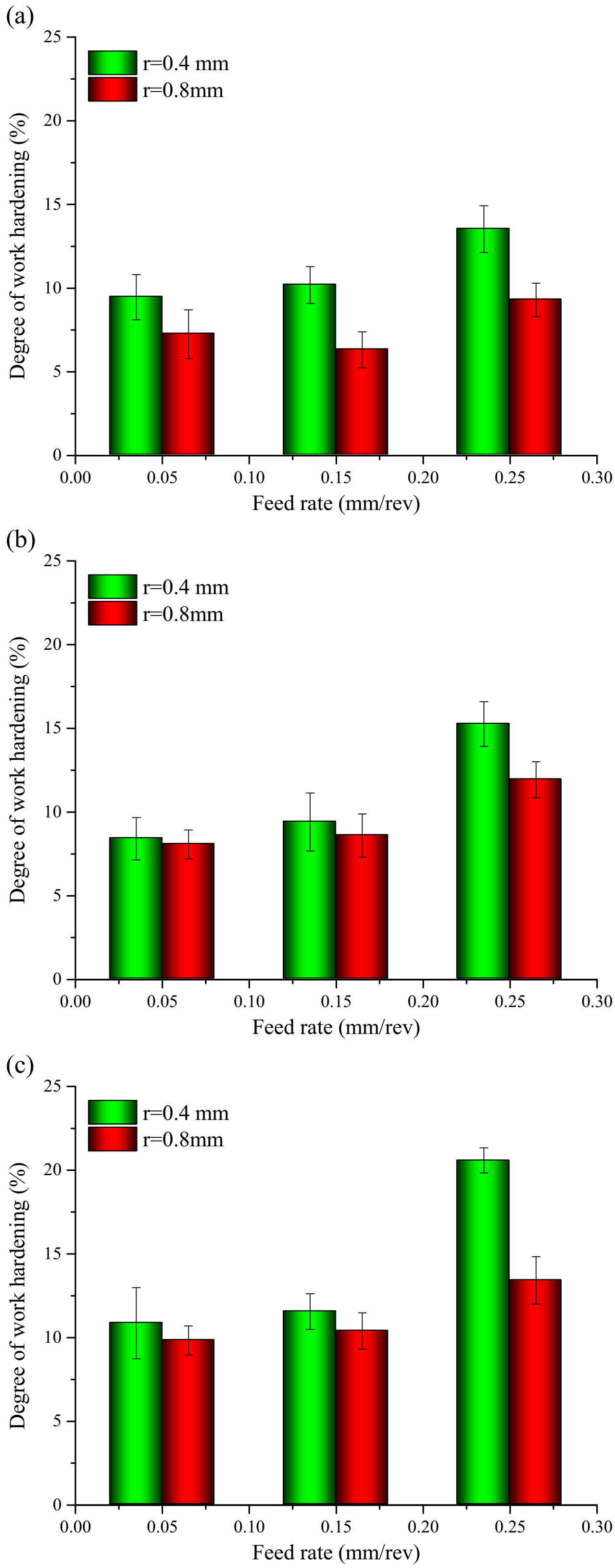


Fig. 9 Effects of tool nose radius on degree of work hardening at **a** Vc = 80 m/min, **b** Vc = 100 m/min, and **c** Vc = 120 m/min

machined surface became higher with a smaller radius of 0.2 mm compared with a larger radius of 0.8 mm.

Sharman et al. [27] proposed that a larger tool nose radius had a similar influence to a negative rake angle, which increased the plowing and squeezing within the cutting zone. This would lead to more severe plastic deformation. As a consequence, in such cases, the degree of work hardening will probably be more reinforced due to the plowing and squeezing.

As the tool nose radius increased, the contact area between the tool and workpiece increased (see in Fig. 5). The tool–workpiece friction increased too. Therefore, the cutting temperature increased due to the friction and resulted in thermal softening on the machined surface to diminish the degree of work hardening.

As a result, an increase in tool nose radius indicated higher temperatures due to friction, which made the degree of work hardening reduce. According to Eqs. (1) and (2), it was indicated that the decreased degree of work hardening due to larger tool nose radius would reduce the fatigue crack propagation threshold value ΔK_{th}. Therefore, the fatigue crack was propagated earlier as the smaller tool nose radius was employed.

4 Conclusions

From the results obtained in the present work and based on current knowledge of mechanical and thermal conditions in dry turning, the following conclusions can be derived:

1. No evident tendency between the cutting speed and surface roughness could be found. It was indicated that the cutting speed was not the dominant factor affecting surface roughness within the cutting conditions investigated.
2. The feed rate and tool nose radius were the dominant factors influencing surface roughness. The increase in the cutting load to the cutting edge as the higher feed rate was employed induced more severe plastic deformation resulting in a higher surface roughness. The larger tool nose radius (0.8 mm) induced much lower surface roughness compared with the smaller tool nose radius (0.4 mm). This was attributed to the increase in contact length between the tool and workpiece, which diminished the residual height of feed marks.
3. There was no significant difference in the depth of work hardening under various cutting speed conditions. Nevertheless, the degree of work hardening could be strengthened as the cutting speed increased. Furthermore, it could be concluded that the fatigue crack propagation threshold increased with the increased cutting speed.
4. Both the depth of work hardening and the degree of work hardening increased with the increase of feed rate. An

increase in feed rate generated higher cutting force, which indicated that more severe plastic deformation generated. And it also increased the compressive zone in the region below the cutting edge. Hence, the higher feed rate generated deeper depth of work hardening and greater degree of work hardening. It is suggested that mechanical effect was the dominant factor in the generation of work hardening compared with the thermal effect.

5. The smaller tool nose radius induced deeper depth of work hardening and greater degree of work hardening. An increase in tool nose radius indicated that the contact area between the tool and workpiece also increased. It is suggested that the tool–workpiece friction increased. Therefore, the cutting temperature increased due to friction and resulted in thermal softening on the machined surface to diminish the degree of work hardening. In addition, the fatigue crack propagation threshold decreased as the larger tool nose radius was employed. It was indicated that the fatigue crack was propagated earlier during service.

Funding information The authors would like to acknowledge the financial support from the National Natural Science Foundation of China (51425503 and 51375272) and the Major Science and Technology Program of High-end CNC Machine Tools and Basic Manufacturing Equipment (2015ZX04005008). This work was also supported by grants from Taishan Scholar Foundation (TS20130922).

References

1. Ulutan D, Ozel T (2011) Machining induced surface integrity in titanium and nickel alloys: a review. Int J Mach Tools Manuf 51(3): 250–280
2. Thakur A, Gangopadhyay S (2016) State-of-the-art in surface integrity in machining of nickel-based super alloys. Int J Mach Tools Manuf 100:25–54
3. Arunachalam R, Mannan MA (2000) Machinability of nickel-based high temperature alloys. Mach Sci Technol 4(1):127–168
4. Ezugwu EO, Bonney J, Yamane Y (2003) An overview of the machinability of aeroengine alloys. J Mater Process Technol 134(2):233–253
5. Shahzad M, Chaussumier M, Chieragatti R, Mabru C, Aria FR (2010) Influence of surface treatments on fatigue life of Al 7010 alloy. J Mater Process Technol 210(13):1821–1826
6. Moussaoui K, Mousseigne M, Senatore J, Chieragatti R (2015) The effect of roughness and residual stresses on fatigue life time of an alloy of titanium. Int J Adv Manuf Technol 78(1–4):557–563
7. Sharman ARC, Hughes JI, Ridgway K (2004) Workpiece surface integrity and tool life issues when turning Inconel 718™ nickel based superalloy. Mach Sci Technol 8(3):399–414
8. Arunachalam RM, Mannan MA, Spowage AC (2004) Residual stress and surface roughness when facing age hardened Inconel 718 with CBN and ceramic cutting tools. Int J Mach Tools Manuf 44(9):879–887
9. Pawade RS, Joshi SS, Brahmankar PK (2008) Effect of machining parameters and cutting edge geometry on surface integrity of high-speed turned Inconel 718. Int J Mach Tools Manuf 48(1):15–28
10. Thakur DG, Ramamoorthy B, Vijayaraghavan L (2012) Effect of cutting parameters on the degree of work hardening and tool life during high-speed machining of Inconel 718. Int J Adv Manuf Technol 59(5–8):483–489
11. Coelho RT, Silva LR, Braghini A, Bezerra AA (2004) Some effects of cutting edge preparation and geometric modifications when turning INCONEL 718™ at high cutting speeds. J Mater Process Technol 148(1):147–153
12. Bushlya V, Zhou J, Ståhl JE (2014) Modeling and experimentation on multistage work-hardening mechanism in machining with nose–radiused tools and its influence on machined subsurface quality and tool wear. Int J Adv Manuf Technol 73(1–4):545–555
13. Ezilarasan C, Velayudham A (2013) Effect of machining parameters on surface integrity in machining Nimonic C-263 super alloy using whisker-reinforced ceramic insert. J Mater Eng Perform 22(6):1619–1628
14. Umbrello D (2013) Investigation of surface integrity in dry machining of Inconel 718. Int J Adv Manuf Technol 69(9–12):2183–2190
15. Zhou J, Bushlya V, Avdovic P, Ståhl J (2012) Study of surface quality in high speed turning of Inconel 718 with uncoated and coated CBN tools. Int J Adv Manuf Technol 58(1):141–151
16. Devillez A, Le CG, Dominiak S, Dudzinski D (2011) Dry machining of Inconel 718, workpiece surface integrity. J Mater Process Technol 211(10):1590–1598
17. Thakur A, Mohanty A, Gangopadhyay S (2014) Comparative study of surface integrity aspects of Incoloy 825 during machining with uncoated and CVD multilayer coated inserts. Appl Surf Sci 320: 829–837
18. Nalbant M, Altın A, Gökkaya H (2007) The effect of coating material and geometry of cutting tool and cutting speed on machinability properties of Inconel 718 super alloys. Mater Des 28(5):1719–1724
19. Dufrenoy S, Bacroix B, Chauveau T, Lemaire, I, Guillemot N, Thomas G (2015) Influence of surface integrity on fatigue limit: Ti-10V-2Fe-3Al titanium application. Proceedings of the 13th World Conference on Titanium. John Wiley & Sons Inc pp:1587–1592
20. Ren XP, Liu ZQ (2016) Influence of cutting parameters on work hardening behavior of surface layer during turning superalloy Inconel 718. Int J Adv Manuf Technol 86(5–8):2319–2327
21. Madariaga A, Esnaola JA, Fernandez E, Arrazola PJ, Garay A, Morel F (2014) Analysis of residual stress and work-hardened profiles on Inconel 718 when face turning with large-nose radius tools. Int J Adv Manuf Technol 71(9–12):1587–1598
22. Murakami Y (2002) Metal fatigue: effects of small defects and nonmetallic inclusions. Elsevier
23. Outeiro JC, Dias AM, Lebrun JL (2004) Experimental assessment of temperature distribution in three-dimensional cutting process. Mach Sci Technol 8(3):357–376
24. Navas VG, Gonzalo O, Bengoetxea I (2012) Effect of cutting parameters in the surface residual stresses generated by turning in AISI 4340 steel. Int J Mach Tools Manuf 61:48–57
25. Yang QB, Liu ZQ, Wang B (2012) Characterization of chip formation during machining 1045 steel. Int J Adv Manuf Technol 63(9): 881–886
26. Sasahara H (2005) The effect on fatigue life of residual stress and surface hardness resulting from different cutting conditions of 0.45% C steel. Int J Mach Tools Manuf 45(2):131–136
27. Sharman ARC, Hughes JI, Ridgway K (2015) The effect of tool nose radius on surface integrity and residual stresses when turning Inconel 718™. J Mater Process Technol 216:123–132