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Surface integrity and fatigue behavior when turning γ-TiAl alloy with optimized PVD-coated carbide inserts

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Tool wear

Abstract This paper presents a comprehensive investigation on the effects of tool and turning parameters on surface integrity and fatigue behavior in turning γ-TiAl alloy. The wear of inserts surface, cutting forces, and surface roughness were studied to optimize PVD-coated carbide inserts. Surface topography, residual stresses, microhardness, and microstructure were analyzed to characterize the surfaces layer under different turning parameters. Surface integrity and fatigue life tests of γ-TiAl alloy were conducted under turning and turning-polishing processes. The results show that compared to CNMG120412-MF4, CNMG120408-SM is more suitable because it obtained low cutting force, surface roughness, and tool wear. With increasing the cutting speed and depth, the depths of the compressive residual stress layer, hardening layer, and plastic deformation layer increased. For turning and turning-polishing specimens, the compressive residual stress was relaxed by less than 20–30% after 10^7 cycles. The fatigue life of a turning-polishing specimen with $R_a = 0.15$ μm has increased 3 times from that of a turning specimen with $R_a = 0.43$ μm.

1. Introduction

Light and thermal-stability alloy materials have received attentions in the aeroengine field. γ-TiAl alloy is mainly formed by titanium and aluminum. Ti and Al elements in γ-TiAl alloy can effectively improve its mechanical and thermodynamic performance. γ-TiAl alloy is used in engine components which are working under 800 °C temperature, instead of nickel-based superalloy. γ-TiAl alloy has good mechanical properties, for example, high specific strength, elastic modulus, low density, and good oxidation resistance, and these characteristics make it suitable in the aircraft engine area, including turbines, compressor blades, etc.[1,2] Its low density can effectively reduce the weight of an engine, thus reducing the inertia of rotating parts, which is beneficial to the rotating parts. Despite that γ-TiAl alloy has attractive mechanical and thermal properties, it also

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has some bad material properties, such as poor ductility, thermal conductivity, fracture toughness, high brittleness, and easiness to react with tool materials.[3] The main problems of γ-TiAl are lamellae deformation, surface micro cracks, and higher surface roughness and residual stresses.[4] These defects will become initial crack extension points, eventually leading to a workpiece failure.

Domestic and overseas scholars have carried out a lot of research on the surface integrity of turning γ-TiAl alloy. Zhang[5] have found that the machining ability of an uncoated negative rake hard alloy cutter is better. Adhesion wear is the main wear form of cutting tools. Mantle and Aspinwall[6,7] have found that when turning γ-TiAl alloy, the defects of surface integrity include material pull out, surface drag, and surface hardening and cracking. A crack will reduce fatigue life, and there is no expansion of the crack; optimizing processing parameters can reduce surface defects. Sharman et al.[8] have found that surface damages included lamellae deformation, surface hardening, and broken TiB_2. Under the conditions of little cutting depth and feed, the cracks size could be reduced. The lubrication condition and cutting speed had little influence on cutting forces, while the cutting depth had the most influence on all three cutting forces. Klocke et al.[9,10] have systematically studied the influences of different turning parameters, insert geometry, and lubrication conditions on the cutting surface roughness and tool wear. Considering the surface quality, machining of γ-TiAl can be intensified by changing the parameters and insert geometry. The cutting depth has a smaller effect on the surface roughness than the corner radius r_ε. When the feed is reduced, the roughness will decrease with an approximately linear trend. A higher cutting speed results in more severe tool wear, and higher surface quality has been found when using tools RCMX ($r\varepsilon$ = 0.6 mm) than that using tools CNMA ($r\varepsilon$ = 0.8 mm) in dry conditions. Tools RCMX are round, the radial relief angle is 7°, the tolerance grade is M, and X represents the shape of the screw hole. As for tools CNMA, the rhombus apex angle is 80°, the clearance angle is 0°, and the form of chip breaker is MA. Beranoagirre et al.[11] have found that the cutting speed affects more on tool wear than on feeding and an increase of the cutting speed leads to worse tool wear. Ma[12] has found that the machining ability of physical vapor deposition (PVD)-coated hard alloy cutters is better. Wan et al.[13] reviewed the high-cycle fatigue behavior of γ-TiAl alloy. The formation and microstructure of γ-TiAl alloy are the key factors that affect its fatigue strength. Xue et al.[14] carried out a bending fatigue test on γ-TiAl alloy at room temperature. The results show that when the fatigue cycles are more than 10^7, the fatigue fracture is still occurring, and the surface roughness has little effect on the fatigue life. Fatigue damage often occurs at the stress concentration of the building surface. Lin et al.[15] studied the residual stress relaxation of the surface after shot peening in a fatigue test and found that the residual stress produced at the beginning of the test was faster and the residual stress was stable after 10^3 cycles of fatigue.

In most of these studies, in terms of γ-TiAl, only the relationship between surface damage, roughness, and turning parameters are analyzed, lacking studies on the influences of parameters on roughness, residual stress, microhardness, and microstructure. Previous research has not been able to explore the effects of turning parameters on the metamorphic layer, let alone conclusions between turning parameters and surface integrity. The influences of tool and turning parameters on surface integrity, including residual stress, surface roughness, microhardness, and surface topography, were studied in this paper when turning γ-TiAl by using PVD-coated carbide inserts. This study plays a guiding significance on obtaining high surface quality and promotes the applications of γ-TiAl.

2. Materials and methods

2.1. Workpiece material

Extrusion forming γ-TiAl alloy was used in this study. The main chemical components are shown in Table 1. γ-TiAl alloy has good mechanical properties under high temperatures,[7] as shown in Table 2.

2.2. Experimental details

Cutting force and tool wear tests were conducted to investigate the effects of tool geometric parameters on the cutting force and tool wear under the condition of v_c = 30 m/min, a_p = 0.6 mm, f = 0.08 mm/r. Experiments were performed using a CK7525 numerical controlled lathe. SANDVIK and SECO carbide blades were used in the study. Geometric parameters of SANDVIK and SECO carbide blades are shown in Table 3. The SANDVIK carbide blade is PVD-TiCN coating, the rake angle is −13°, the clearance angle is 0°, the corner radius is 0.8 mm, and the chip breaker is SM style. The SECO carbide blade is PVD-TiAlN coating, the rake angle is −13°, the clearance angle is 0°, the corner radius is 1.2 mm, and the chip breaker is MF4 style.

The effects of turning parameters on surface roughness and morphology were also obtained when using three different tools. The specific turning parameters are given in Table 4. The influences of turning parameters on the altered layer was studied when using a CNMG120408-SM tool under different turning parameters. A fatigue specimen with a length of 52 mm is shown in Fig. 1. As shown in Fig. 1, σ_{rx} describes the residual stress along the x-axis and σ_{ry} is the residual stress along the y-axis. The two kinds of processes are turning and turning-polishing. The turning parameters are rotation speed n = 1000 r/min, feed f = 0.06 mm/r, and axial cutting depth a_p = 0.2 mm. Specimens were machined using CNMG120408-SM cutting tools. The polishing method was used until the turning mark and blasting crater were out of sight. Fatigue tests were conducted on a rotating bending fatigue testing machine QBWP-10000, at room temperature, with a sinusoidal load, the frequency of which was 100 Hz; the cycle stress ratio $R = -1$; the stress level was 1000 MPa. Stress relaxation tests were conducted on the same testing machine with a stress level of 410 MPa, and residual stresses tests were conducted under different cycle tests.

2.3. Cutting force and surface integrity testing

Cutting force tests were conducted by a three-component piezo-electric dynamometer type 9255B with a resonant frequency of 1.7 kHz. The dynamometer was mounted on the worktable under the tool and connected to a charge amplifier Kistler5080A. The amplified cutting forces signal was acquired

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