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The Effect of Milling Cooling Conditions on the Surface Integrity and Fatigue Behavior of the GH4169 Superalloy

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Abstract: The GH4169 superalloy has high strength at high temperatures. Cooling conditions have a major impact on the machined surface integrity, which further affects the fatigue properties of specimens of the GH4169 superalloy. The influence of cooling conditions on the surface integrity of the GH4169 superalloy is first studied during the side milling. Then, the effect of surface integrity under different cooling conditions on the fatigue behavior of specimens of the GH4169 superalloy is investigated by a standard tensile and tensile–mode fatigue testing. The results obtained show that surface roughness and the depth of the plastic deformation layer in wet milling and dry milling makes little difference, the surface microhardness rate in dry milling is slightly lower than that in wet milling, the surface tensile residual stress in dry milling is significantly higher than that in wet milling, and the fatigue behavior in dry milling is only about 50% of that in wet milling. In addition, the crack initiation of specimens of the GH4169 superalloy utilizing wet milling is on the subsurface, while that from dry milling is on the surface. Thus, cooling conditions have an important impact on the fatigue behavior of specimens of the GH4169 superalloy, and micro defects in dry milling are the main factors of decreasing of fatigue behavior of specimens of the GH4169 superalloy.

Keywords: cooling condition; surface integrity; fatigue life; GH4169

1. Introduction

The GH4169 superalloy has been widely used in aerospace, aviation, and other industries due to its excellent properties [1–5]. However, its properties are difficult to fully utilize in machining. Furthermore, the main challenges when machining the GH4169 superalloy are the short tool life and thermal damage [6–10]. Therefore, researchers have undertaken a lot of studies on tool wear and cooling conditions when machining the GH4169 superalloy. Guo et al. [8] pointed out that higher tool wear produced less surface roughness in end milling, and the fatigue behavior of specimens of the GH4169 superalloy after end milling was not necessarily affected by tool wear, which was between 0 and 0.2 mm. Zhou et al. [9] studied the influence of minimum quantity lubrication (MQL) on cutting force and tool wear during machining of the GH4169 superalloy. The experimental results showed that MQL effectively decreased the cutting temperature compared to dry cutting and conventional cutting. Meanwhile, the magnitude of the cutting force and the quality of the surface finish were directly affected by tool wear. Iturbe et al. [10] investigated the surface integrity of GH4169 superalloy in turning with conventional and cryogenic cooling. The results showed that the surface integrity was significantly affected by tool flank wear, and the tool life of conventional cooling was longer than that of cryogenic cooling.
cooling. Musfirah et al. [11] revealed that the surface roughness of the GH4169 superalloy in cryogenic coolant was significantly lower than that in a dry coolant after end milling. In addition, compared to dry milling, the depth of the plastic deformation layer in a cryogenic coolant utilizing end milling decreased obviously. Pereira et al. [12] investigated the influence of CryoMQL_CO2 (cryogenic machining using minimum quantity of lubrication and carbon dioxide) and dry machining on the tool wear and surface integrity of AISI 304 in turning. The experimental results showed that the tool life of CryoMQL_CO2 was 30% higher than that with dry machining. In addition, compared with dry machining, CryoMQL_CO2 had a lower surface roughness, surface hardness, and depth of the plastic deformation layer. In addition, Pereira et al. [13] studied the effect of different cooling conditions on the GH4169 superalloy of milling, and pointed out that the tool life of wet machining, internal CryoMQL_CO2, external CryoMQL_CO2, and MQL is reduced in turn. Suárez et al. [14,15] claimed that HPC (high-pressure cooling) could lead to a more than 30% reduction on the tool flank wear, and decrease the cutting force by more than 10% in the machining of the GH4169 superalloy. The surface integrity of the GH4169 superalloy of end milling was studied by Cai et al. [16]. The results showed that MQL decreased the surface roughness and produced residual surface compressive stress in milling, but surface residual stress gradually became smaller and was transformed into residual surface tensile stress as the tool flank wear increased. Furthermore, residual surface tensile stress was produced directly in the absence of a cutting fluid. Mohsan et al. [17] showed the surface integrity of the GH4169 superalloy under different cooling conditions. The surface integrity of the GH4169 superalloy of flood cooling turning was better than that of dry turning at lower cutting speeds, but flood cooling turning had a low impact on the surface integrity of the GH4169 superalloy at higher cutting speeds due to the bubble barrier or seizure effect that hinders heat transfer between the coolant and the workpiece. In addition, turning of the GH4169 superalloy under high-pressure cooling yielded great surface roughness with lower surface tensile residual stress at higher cutting speeds.

Many scholars have only conducted positive research about surface integrity. The influence of cooling conditions on the fatigue behavior of specimens of the GH4169 superalloy has been investigated in few studies. Therefore, it is obviously significant to investigate the effect of cooling conditions on the fatigue behavior of specimens of the GH4169 superalloy. Based on the experimental results, fatigue behavior and surface integrity (such as surface roughness, surface topography, surface microhardness rate, surface residual stress, and microstructure) were further studied under different cooling conditions in this paper.

2. Experimental

2.1. Materials

The workpiece material used in all experiments was the GH4169 superalloy created by solution-aging treatment. The rough material used for this study was heat-treated at 960 °C for 1 h, subjected to water or air cooling, aged at 720 °C for 8 h, subjected to furnace cooling, aged at 620 °C for 8 h, and then air-cooled. The chemical composition and mechanical properties of the specimen material are listed in Tables 1 and 2, respectively.

2.2. Conditions and Process of Milling Experiment

All milling experiments were carried out on a VMC 850E four-axis vertical CNC machining center (Shenyang Machine Tool Plant, Shenyang, China). The clamping and processing of the specimens of the GH4169 superalloy were shown in Figure 1. Due to the material and shape of specimens of the GH4169 superalloy, AlTiN-coated cemented carbide side and down milling cutters with four teeth were used. The diameter of the milling tool was 10 mm. The specimen was processed by the side and down milling process, as shown in Figure 2.
Table 1. The chemical composition of the GH4169 superalloy (unit: %).

|   | C   | Nb  | Si  | Mn  | Cr     | Ti  | Al     | Mo  | Ni  | Cu  | Co  | Fe |
|---|-----|-----|-----|-----|--------|-----|--------|-----|-----|-----|-----|----|
|   | 0.08| 4.75–5.5 | 0.35 | 0.35 | 17–20 | 0.75–1.15 | 0.3–0.7 | 2.8–3.3 | 50–55 | 0.3 | 1.0 | Balance |

Table 2. The mechanical properties of the GH4169 superalloy.

|                  | Tensile Strength/MPa | Elastic Modulus/GPa | Elongation/% | Hardness/HV | Thermal Conductivity/(W/m°C) | Shrinkage/% |
|------------------|----------------------|--------------------|--------------|-------------|------------------------------|-------------|
|                  | 1280                 | 205                | 15           | 423         | 14.65                        | 41          |

As shown in Figure 3, two stable worn cutters with a flank wear of 0.05 mm and 0.20 mm were used in the experiment to enhance the reliability of the experimental results. The machining parameters (tool flank wear VB, cutting speed \( v_z \), feed rate \( f_z \), cutting width \( a_c \)) are shown in Table 3.

Surface roughness along the feed direction was analyzed using a Time 3220 surface roughness tester (Beijing Times High Technology Co., Ltd., Beijing, China). During the measuring operations, the sampling length was 0.8 mm, the assessing length was 5.6 mm, and the value was obtained by averaging five measurements. Surface topography was observed by a QUANTA 200 scanning electron microscope (SEM) (FEI, Hillsboro, OR, America). The surface microhardness rate was obtained using a FM-800 Microhardness tester (FUTURE-TECH, Tokyo, Japan), in which the loading force was 1.96 N and the loading time was 10 s. Surface residual stress measurements were taken using X-ray diffraction. A Denver-Proto iXRD 3000 (Proto, Oldcastle, ON, Canada) residual stress analyzer with a \( V\alpha \) radiation tube was used. The diffraction angle was 139.69°, the exposure time was 60 s, and the aperture diameter was 1 mm. The metallography structure and fatigue fracture of specimens of the GH4169 superalloy were obtained using a QUANTA 200 scanning electron microscope (SEM) (FEI, Hillsboro, OR, USA).
in a secondary electron (SE) mode. All fatigue experiments were carried out on a high-frequency tensile and tensile–mode fatigue testing machine (Sinotest Equipment Co., Ltd., Changchun, China); the loading frequency was 80-250 HZ, the cyclic stress ratio was 0.1 and the experimental temperature was room temperature. The maximum tensile stress was 1030 MPa [18], which was 80.5% of the tensile strength (1280 MPa). In order to improve the accuracy of the fatigue behavior of specimens, five fatigue experiments were conducted for each set of milling parameters.

![Tool flank wear](image)

**Figure 3.** Tool flank wear. (a) VB = 0.05 mm, (b) VB = 0.20 mm.

| Number | Cooling Conditions | VB/mm | \(v_{e}/(m/min)\) | \(f_{z}/(mm/z)\) | \(a_{e}/mm\) |
|--------|--------------------|-------|-------------------|-----------------|-------------|
| 1      | Wet milling        | 0.05  | 20                | 0.10            | 0.1         |
| 2      | Wet milling        | 0.20  |                   |                 |             |
| 3      | Dry milling        | 0.05  |                   |                 |             |
| 4      | Dry milling        | 0.20  |                   |                 |             |

### 3. Results and Discussion

#### 3.1. Surface Roughness and Topography

The effect of cooling conditions on the surface roughness along the feed direction is shown in Figure 4. \(R_a\) is the contour arithmetic mean deviation and \(R_z\) is the 10-point height of irregularities. When tool flank wear VB = 0.05 mm, cooling conditions have little impact on surface roughness \(R_a\) and \(R_z\). \(R_a\) is 0.44 \(\mu m\) and \(R_z\) shows only a difference of 0.1 \(\mu m\) between wet milling and dry milling. When tool flank wear increases to 0.20 mm, the surface roughness \(R_a\) of specimens of the GH4169 superalloy after wet milling and dry milling are 0.79 \(\mu m\) and 0.67 \(\mu m\), respectively, and the surface roughness \(R_z\) of specimens of the GH4169 superalloy after wet milling and dry milling are 3.40 \(\mu m\) and 2.45 \(\mu m\), respectively. The results show that the surface roughness of dry milling increases less than that of wet milling. With the increase in tool flank wear, the cutting temperature of dry milling rises faster, making it more prone to build-up edge when milling, which results in a lower roughness of the milling surface than by wet milling [19].

The influence of cooling conditions on surface topography is shown in Figure 5. Surface topographies after wet milling and dry milling are relatively flat. With a microscope at a magnification of 2000×, micro defects and adherent chips are found in the surface topography after dry milling, as shown in Figure 6. Due to the lack of cooling of the cutting fluid, the tool rake face adhered to processed chips, which attach to the surface of specimens of the GH4169 superalloy, and was softened or even liquefied at high temperature during subsequent processing [20]. Meanwhile, when tool teeth are cut out, workpiece materials adhered to the tool teeth are separated from the surface of workpieces, which may be torn to produce surface micro defects, as shown in Figure 6.
Meanwhile, with the increase in the tool flank wear, the cutting temperature rises to 16.48% under the condition of VB dry milling shows an obvious decrease. The surface microhardness rate decreases from 21.28% to 9.92% under the condition of VB = 0.05 mm, and from 19.65% to 14.01% under the condition of VB = 0.20 mm. As the cutting temperature of dry milling rises significantly, the machined surface is softened or even liquefied. (Figure 4)

Figure 4. Effect of cooling conditions on surface roughness (tool flank wear: VB = 0.05 mm, VB = 0.20 mm). (a) $R_a$, (b) $R_z$.

Figure 5. Surface topography after different cooling conditions. (a) Surface topography of wet milling, (b) Surface topography of dry milling.

Figure 6. Partial enlargement of surface topography after dry milling.

3.2. Surface Microhardness Rate

Figure 7 shows the distribution of surface microhardness rate of workpieces after different cooling conditions. Compared to wet milling, the surface microhardness rate of machined surfaces utilizing dry milling shows an obvious decrease. The surface microhardness rate decreases from 21.28% to 16.48% under the condition of VB = 0.05 mm, and from 19.65% to 14.01% under the condition of VB = 0.20 mm. As the cutting temperature of dry milling rises significantly, the machined surface is softened. Meanwhile, with the increase in the tool flank wear, the cutting temperature rises.
further [21], causing the surface microhardness rate to continue to reduce. Thus, when the tool flank wear increases from 0.05 mm to 0.20 mm, the surface microhardness rate after dry milling declines by 2.47%, while the surface microhardness rate after wet milling decreases by only 1.63% due to the effect of the cooling of the cutting fluid.

3.3. Surface Residual Stress

The distribution of surface residual stress along the feed direction under different cooling conditions is shown in Figure 8. Under the condition of VB = 0.05 mm, the surface residual stress is 73 MPa after wet milling, while the surface residual stress is 412 MPa after dry milling. Under the condition of VB = 0.20 mm, the surface residual stress after wet milling and dry milling is 187 MPa and 498 MPa, respectively. Residual surface tensile stresses are produced in all machined surfaces. Compared to wet milling, the residual surface tensile stress after dry milling increases significantly. At the same time, with tool flank wear increasing, the residual surface tensile stress rises enormously.

3.4. Microstructure

Figure 9 shows the influence of cooling conditions on microstructure. The plastic deformation layer along the tool feed direction observed on the subsurface during all processes is caused by the thermal and mechanical effects of machining. Comparing Figure 9a,b, when VB = 0.05 mm, the depth of the plastic deformation layer of specimens of the GH4169 superalloy after wet milling is about 5.5 μm and the depth of the grained layer of specimens of the GH4169 superalloy after dry milling is about 5.4 μm. With VB increasing to 0.20 mm, the depth of the plastic deformation layer after
wet milling and dry milling increases to 9.7 µm and 9.4 µm, as shown in Figure 9c,d respectively. As can be seen, with tool flank wear increasing, the depth of the plastic deformation layer rises significantly, while cooling conditions have little impact on it.

Figure 9. Microstructure of specimens of GH4169 superalloy under different cooling conditions; (a) VB = 0.05 mm (wet milling), (b) VB = 0.05 mm (dry milling), (c) VB = 0.20 mm (wet milling), (d) VB = 0.20 mm (dry milling).

3.5. Fatigue Behavior

The influence of cooling conditions on the fatigue behavior of specimens of GH4169 superalloy is shown in Figure 10. When VB is 0.05 mm, the fatigue behavior of specimens of the GH4169 superalloy after wet milling and dry milling are $2.42 \times 10^5$ and $1.36 \times 10^5$ cycles at the same stress level, respectively. The fatigue behavior of specimens of the GH4169 superalloy utilizing wet milling is 78.32% higher than that utilizing dry milling. When VB is 0.20 mm, the fatigue behavior of specimens of the GH4169 superalloy after wet milling is $2.18 \times 10^5$ cycles, and the fatigue life of specimens of the GH4169 superalloy after dry milling is $7.58 \times 10^4$ cycles. The fatigue behavior of specimens of the GH4169 superalloy of dry milling is only 34.88% of that of wet milling. It can be concluded that the fatigue behavior of specimens of the GH4169 superalloy after wet milling is significantly higher than that after dry milling. In addition, when VB increases from 0.05 mm to 0.20 mm, the fatigue life of specimens of the GH4169 superalloy utilizing dry milling decreases by 44.1%, while that utilizing wet milling only reduces by 10.13%.

Figure 11 shows fatigue fracture in milled specimens of the GH4169 superalloy with different cooling conditions. The crack initiation of wet milling, shown in Figure 11a,b, starts at the subsurface,
while the crack initiation of dry milling, shown in Figure 11c,d, is on the surface. Meanwhile, it can be seen that the surface of dry milling is adhered to by chips.

![Fatigue life of milled specimens of the GH4169 superalloy with different cooling conditions.](image)

**Figure 10.** Fatigue life of milled specimens of the GH4169 superalloy with different cooling conditions.

![Fatigue fracture after milled workpieces with different cooling conditions](image)

**Figure 11.** Fatigue fracture after milled workpieces with different cooling conditions: (a) VB = 0.05 mm (wet milling), (b) VB = 0.05 mm (dry milling), (c) VB = 0.20 mm (wet milling), (d) VB = 0.20 mm (dry milling).

Based on the above analysis, with tool flank wear increasing, the surface roughness, surface residual stress, and depth of the plastic deformation layer of a machined surface after wet milling and dry milling increase significantly, except for the surface microhardness rate. The fatigue behavior of
specimens of the GH4169 superalloy in wet milling only decreases by 10.13%, while that of specimens of the GH4169 superalloy of dry milling is nearly halved.

In terms of cooling conditions, when the tool flank wear is constant, compared with wet milling, the surface roughness of dry milling is hardly different; the residual surface tensile stress of dry milling rises significantly, the surface microhardness rate of dry milling decreases a little, and the fatigue behavior of specimens of the GH4169 superalloy of dry milling declines tremendously.

As can be seen by observing the fracture topography, the crack initiation of wet-milled specimens of the GH4169 superalloy is on the subsurface. The direction of surface roughness during side milling is the same as the fatigue loading direction, so the influence of surface roughness on the fatigue behavior of specimens of the GH4169 superalloy of wet milling can be ignored. Therefore, the slight downward trend of fatigue behavior of specimens of the GH4169 superalloy after wet milling is caused by the rise in residual surface tensile stress with the increase in tool flank wear.

The crack initiation of specimens of the GH4169 superalloy of dry milling is on the surface. The influence of surface conditions on the fatigue behavior of specimens of the GH4169 superalloy is the main factor. Since the surface roughness of wet milling and dry milling is similar, surface micro defects and adherent chips of surface topography caused by the lack of cooling of cutting fluid have a critical impact on the fatigue behavior of specimens of the GH4169 superalloy. In addition, with the absence of cooling and cutting fluid, the high cutting temperature of dry milling causes the residual surface tensile stress to improve sharply, which decreases the fatigue behavior of specimens of the GH4169 superalloy. Thus, the cooling condition is the essential factor that makes the fatigue behavior of specimens of the GH4169 superalloy of dry milling be lower than that of specimens of the GH4169 superalloy of wet milling.

4. Conclusions

1. Cooling conditions have a direct impact on the surface integrity of the milled GH4169 superalloy. Microdefects formed by adherent chips of surface topography on the dry milling surface are the main reason that the fatigue behavior of specimens of the GH4169 superalloy of dry milling is lower than that with wet milling.

2. In the case of side milling, surface roughness along the fatigue loading direction has no significant impact on the fatigue behavior of specimens of the GH4169 superalloy after wet milling and dry milling. The improvement in residual surface tensile stress is the predominant factor in the fatigue behavior of the GH4169 superalloy specimens, with wet milling slightly decreasing while specimens’ fatigue behavior utilizing dry milling is mainly influenced by surface micro defects and adherent chips of surface topography. A minor factor in the fatigue behavior of dry milling is the increase in surface residual stress and the decrease in the surface microhardness rate.

3. Compared with wet milling, the process of dry milling has little impact on surface roughness and the depth of the plastic deformation layer. However, it can lead to an increase in the residual surface tensile stress and a decrease in the surface microhardness rate, and produce surface micro defects and adherent chips of surface topography.

4. With the increase in tool flank wear, the surface integrity of wet milling and dry milling follows the same trend, by which surface roughness increases, the surface microhardness rate experiences little change, the residual surface tensile stress rises immensely, and the depth of the plastic deformation layer increases significantly.

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