Evaluation of workpiece surface integrity following creep feed grinding of single-crystal nickel based alloy DD6

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Abstract: In this article, tests were carried out to evaluate the workpiece surface integrity in creep feed grinding of single-crystal nickel based alloy DD6, with micro-crystal alumina (MA) and brown alumina (BA) abrasive wheels, respectively. Changes in the wheel topography, surface roughness, microhardness, as well as metallography of workpieces were evaluated by means of optical microscope, scanning electron microscope (SEM), microhardness tester etc. The results are summarized as following: (1) The main wear pattern of alumina wheels was determined as wheel clogging during grinding of DD6. (2) Surface roughness was typically higher by up to ~50% on DD6 ground by BA wheel due to great wheel clogging and workpiece tearing and scratching. (3) The depth of affected layer was extended to ~10 µm and surface hardening up to ~430 HV0.05 occurred when creep feed grinding of DD6 using BA wheel. In contrast, ground DD6 surface showed slightly marginal hardening behavior with MA wheel.

Keywords: Surface integrity, Creep feed grinding, Single-crystal nickel based alloys DD6

1 Introduction

Nickel based alloys, especially the cast ones like single-crystal nickel based alloys, have been widely employed for manufacturing gas turbine blades in advanced aeroengine, due to their superior creep resistance and high strength during withstanding huge mechanical loads at extremely high temperature [1-3]. Since strict geometric conditions have to be fulfilled, particularly at the blade root, the grinding process is of great importance for manufacturing these parts [4]. It is worthwhile mentioning that the grinding surface integrity characteristics directly influence the functional performance by controlling the tribological and mechanical proprieties, such as friction, wear resistance and fatigue crack [1]. The long service life of workpiece is strongly dependent on the surface integrity. Therefore, it is very essential to understand the alteration of surface quality of workpiece during grinding for enhancing resistance to creep and fatigue failure, reliability and durability of the ground component.

In the past decades, extensive research has been dedicated to surface integrity in terms of grinding damage and surface deformation especially for nickel based superalloys (e.g. Inconel 718 [5] and IN738LC [6])and titanium alloys (e.g. Ti-6Al-4V [7] and γ-TiAl [8]). These reports indicate that grinding process can induce severely workpiece surface or subsurface changes, like internal crack[5,6], white layer formation[6], and surface hardening[7,8]. The findings are beneficial to help understand the complicated grinding process and provide a guidance to obtain desirable ground products. However, for DD6, as one available cast nickel based superalloy and prepared by one single crystal without grain boundaries [9], and possessing excellent mechanical and chemical properties, there have been virtually no profound investigations reported on grinding surface integrity so far. In particular, the high temperature strength, easy hardening and low heat conductivity of such superalloy are likely to result in grinding burn and therefore make it one typical difficult-to-cut material. Consequently, it is very urgent to investigate the surface integrity during creep feed grinding of DD6 for the sake of exploring the great potential as much as possible.

In the current experiments, micro-crystal alumina (MA) and brown alumina (BA) abrasive wheels were utilized as the grinding tools in order to comparatively investigate the surface integrity of DD6. The
ground surface roughness, topography, microhardness and metallurgical structure were evaluated, respectively. The results are expected to provide an experimental basis for the optimization of the possible profile grinding process.

2 Materials and experimental procedure

The grinding trails were carried out on a 3-axis CNC high-speed machining center (Profinat MT-408, BLOHM) with a spindle rated at 45 kW and a maximum rotational speed of 8000 r/min (Fig.1). The chemical composition and heat treated conditions are shown in tables 1 and 2, respectively. Both micro-crystal alumina (MA) and brown alumina (BA) abrasive wheels were employed with the grain size of 80 US mesh. The experimental conditions are displayed in table 3. After grinding, selected workpiece surfaces were first cut both perpendicular and parallel to the feed direction. Subsequently, the specimens were ground and polished mechanically until the surface roughness was below 0.1 µm and then observed using optical microscope to ensure elimination of thermal damage or surface defects. Microhardness evaluation of these specimens was undertaken with a HXS-1000AK hardness tester using Vickers indenter at a load of 50 g applied for 15 s. Meantime, polished specimens were etched for about 30s using the reagent containing 25 ml H2O+25 ml HNO3+50 ml HCl. The microstructural analysis was undertaken with optical microscope (OM) and scanning electron microscope (SEM).

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Co</th>
<th>Mo</th>
<th>W</th>
<th>Ta</th>
<th>Re</th>
<th>Hf</th>
<th>Al</th>
<th>Ni</th>
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<tbody>
<tr>
<td>wt.%</td>
<td>4.3</td>
<td>9</td>
<td>2</td>
<td>8</td>
<td>7.5</td>
<td>2</td>
<td>0.1</td>
<td>5.7</td>
<td>Bal.</td>
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</table>

<table>
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<th>Workpiece material</th>
<th>Heat treatments</th>
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<tr>
<td>DD6</td>
<td>1290°C/1h (Solution)+1300°C/2h+1315°C/4h, AC+1120°C/4h (Aging treatments), AC+870°C/32h, AC</td>
</tr>
</tbody>
</table>

Table 3 Grinding conditions

<table>
<thead>
<tr>
<th>Grinding method</th>
<th>Plunge up grinding</th>
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</thead>
<tbody>
<tr>
<td>Grinding wheels</td>
<td>Vitrified micro-crystal alumina wheel (5SO80FV45) and brown alumina wheel (80FF22V35)</td>
</tr>
<tr>
<td>Dimensions: Φ400 x 10mm</td>
<td></td>
</tr>
<tr>
<td>Grinding speed $v_g$ (m/s)</td>
<td>25</td>
</tr>
<tr>
<td>Workpiece infeed rate $v_i$ (mm/min)</td>
<td>100</td>
</tr>
<tr>
<td>Grinding depth $a_p$ (mm)</td>
<td>1.2</td>
</tr>
<tr>
<td>Grinding fluid</td>
<td>Water based 5% emulsion</td>
</tr>
<tr>
<td>Workpiece</td>
<td>Single-crystal nickel based alloy DD6</td>
</tr>
<tr>
<td>Dimensions: 30x8x8 mm</td>
<td></td>
</tr>
<tr>
<td>Dressing parameters</td>
<td>Single point diamond</td>
</tr>
<tr>
<td>Dressing speed: 20 m/s, Dressing amount: 0.2mm</td>
<td></td>
</tr>
<tr>
<td>Dressing infeed speed: 100mm/min, Dressing depth: 0.01 mm/red</td>
<td></td>
</tr>
</tbody>
</table>
3 Experimental results and discussion

3.1 Grinding wheel topography

Sample optical micrographs of the particular grinding wheel surfaces after tests are detailed in Fig. 2. Many clogged chips were observed to be mounted on the two wheels, while this was especially prevalent on MA grinding wheels used to machine DD6 (Fig. 2(b)). Generally, the high plasticity of workpiece contributes to material removal during machining. In addition, the abundant heat induced by grinding in the contact area possibly softens the workpiece material. DD6 possesses a relatively high plasticity [9], therefore it can be stated that both the above factors facilitate the formation of long and flexible chips of DD6 material during creep feed grinding process. Here it was also found that the size of clogged chips was about 0.5-1 mm regardless of the grinding wheel type. Due to the high porosity (13 vol.% for MA and BA wheels) of bonding system in grinding wheels, the chips generated during creep feed grinding could flow into the wheel pores. However, because of the limited capacity of these pores, as grinding moved forward, the chips became to twine and subsequently clogged the space if these chips were not removed or cleaned timely. The wheel loads would inevitably increase if wheel self-sharpening or wheel dressing was not well performed. Furthermore, somewhat interestingly, some abrasives of MA wheels were surrounded entirely by the clogged chips from DD6 (marked in Fig. 2(b)). This was most likely due to the difference of abrasive preparation process of grinding wheels, which was an indicative of higher bonding strength of MA wheel as opposed to BA one.

3.2 Workpiece topography and roughness

The optical micrographs of workpieces using different grinding wheels are displayed in Fig. 3. Considerable workpiece scratching induced by abrasive grain was visible on the samples. The profile of scratches on the workpieces’ surface ground by the two wheels was different. Precisely, large texture on surface of workpiece (approximately 150 µm in Fig. 3(a)) was produced when using BA wheel, while this
was in contrast to the fact observed when using MA wheel, which had a size of approximately 50 µm Fig. 3(b). Previous reports indicated that the abrasive grain micro-fracture and flattening are the main wear mechanism controlling the wear of MA and BA grinding wheel, respectively [10]. The favorable wear mechanism of MA wheel usually kept the surface roughness behavior within a limited range of variation even at a high stock removal. Fig. 4 details the measuring results of the workpieces’ surface shown in Fig. 3 by means of several height parameters i.e., Sa (average surface height), Sq (root mean square height), Sp (maximum peak height), Sv (maximum pit height), and Sz (maximum height) following the end of each trial. It was found that the surface roughness Sa took a relatively low value of ~1 µm, though the other parameters like Sp, Sv and Sz were around rather high level, up to ~8.5 µm. The observation of the ground surface in Fig. 3 supported this. The limiting value had a big difference with the average value, which indicated the fluctuation of the values and inevitably degraded the surface integrity. This can be attributed in part to the relatively low elasticity modulus and large plasticity of DD6, which resulted in more workpiece tearing and scratching during grinding [11]. Concerning the grinding wheels, MA could provide ground surfaces with relatively higher quality almost at every height parameters as opposed to BA, most likely due to the self-sharpening behavior of abrasive grain of the former, which was outlined in previous publications [10].

![Fig. 3. Optical micrographs of workpieces using different grinding wheels](image)

![Fig. 4. Workpiece surface height parameters at test cessation](image)

Fig. 5 shows the high resolution micrographs of workpiece surfaces using a scanning electron microscope. It can be seen that workpiece smearing/ material ploughing and scratching were evident on the surfaces, particularly on the DD6 surfaces using BA wheel, as shown in Fig. 5a. Black spot formation was also clearly visible in Fig. 5(a), which was the characteristic of smeared material. This was possibly the result of chemistry diffusion between abrasives and DD6 material at elevated temperature. Normally, the chemical reaction in contact area was usually caused by grinding temperature. Due to the difference in grinding behavior between MA wheel and BA wheel, the grinding temperature may be different even at the same grinding parameters and the surface response was therefore different. It was important to notice
that the exit burr morphology of DD6 differed when grinding at identical conditions. In Fig. 5 (a), the exit burr seemed to be extruded from the bulk material while the material cutting was prominent in Fig. 5(b). The burr size was short and small (about 10-20 µm). As mentioned above, the different wear behavior of grinding wheels resulted in the difference in grinding performance. Meantime, the inherently anisotropic deformation behavior of the DD6 alloy whose body grew by one single crystal, as well as the low elastic modulus and high plasticity [10], probably resulted in the complexity in the grinding response in material removal mechanism. It will be an interesting point to conduct further investigation in the near future.

3.3 Microhardness and metallographic microstructure of ground surface

Fig. 6 detailedly shows the microhardness depth profile plots measured both perpendicular and parallel to the feed direction, respectively. In the parallel direction, the near surface microhardness of the DD6 workpiece increased up to a maximum of ~430 HV0.05 when using BA wheel, which suggested strain hardening occurred. The slightly marginal hardening was observed for DD6 samples when using MA wheel. This was possibly because the grinding temperature induced by BA wheel was higher than that by MA wheel.
However, changes in microhardness perpendicular to the feed direction were less pronounced in the two tests. Cross-sectional micrographs showing the sub-surface workpiece microstructure from selected tests are displayed in Fig. 7. Microstructural smearing and deformation to a depth of 10 µm were visible when operating at creep feed grinding conditions. In contrast, there was minimal damage detected in all of the other DD6 specimens ground by MA wheel.

Conclusion

(1) In the current investigation, the main wear pattern of alumina wheels was determined as wheel clogging when grinding of single-crystal nickel based alloy DD6.
(2) Due to great wheel clogging and workpiece tearing and scratching, surface roughness was typically higher by up to ~50% on DD6 ground by BA wheel compared to MA wheel.
(3) Under current grinding conditions, the depth of grinding affected layer was extended to ~10 µm and surface hardening up to ~430 HV0.05 occurred when creep feed grinding of DD6 using BA wheel. In contrast, ground DD6 surface showed slightly marginal hardening behavior with MA wheel.

Acknowledgments

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References