Optimization of Roughness and Residual Stresses in Path Controlled Grinding of Crankpin

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Abstract

Crankpin is generally subjected to high thermal and cyclic loads when working. Surface roughness and residual stresses greatly influences the final running characteristics of crankpin. Path controlled grinding process has been used in automotive powertrain industry. The grinding conditions are periodically changing between grinding wheel and crankpin due to the existence of the eccentricity of crankpin and constant rotation speed of crankshaft. It leads to the variation of surface roughness and residual stresses on circumference of crankpin. So the optimization of grinding parameters in crankshaft grinding is essential. This paper presents an investigation to evaluate variation of surface roughness and residual stress along circumference in path controlled grinding of crankpin. The effects of the speed and speed ratio were analyzed in detail with constant rotation speed of crankshaft. It is found that up-grinding and down-grinding exist during one revolution cycle. The results show the surface roughness Ra always keeps below 0.25 μm in all the grinding conditions, and the variations of surface roughness are little along circumference. The highly compressive residual stresses level after grinding is obtained on pin bearing. Compared to the variation of roughness, the variation of residual stress along circumference is large. Based on the results, the lower crankshaft rotational speed, lower grinding depth, and higher wheel speed are suggested to be used in the path controlled grinding of crankpin harden by induction surface hardening.

1. Introduction

Crankshaft is the key parts in engine. Due to the special construction of crankshaft, the conventional grinding method processing crankpin is that the crankshaft is held in place by offsetting chucks to align the crankshafts pins with main axis. Using this method, crankpin is processed as centered circle. However, the processing of main journal and pin journal could not be ground in one clamping. With increased demands for high productivity and accuracy, path controlled grinding process, allowing reduction of non-productive time and re-clamping inaccuracies is developed to machine crankshaft.

Path controlled grinding is one of the most preferentially used nontraditional grinding processes to machine the crankshaft in automotive industry. Two independently programmable wheelheads process the main and pin bearing in one clamping simultaneously allowing reduction of non-productive time and prevention of clamping inaccuracies. The contour of crankpin is achieved with the coupling actions both of the eccentrically pin bearing rotation and the grinding wheel linear movement [1]. Compared to external cylindrical plunge grinding, the contact conditions are periodically changing between grinding wheel and crankpin during the grinding process due to the existence of the eccentricity of crankpin with the constant rotation speed of crankshaft.

Crankpins are generally subjected to high thermal and cyclic loads when working [2]. Surface integrity, such as surface topology, surface roughness, residual stresses, hardness, etc., greatly influences the final characteristics of machined parts [3]. As to the stress, the total stresses are a sum of residual stresses in a machine part and of load stresses produced by the action of external forces and moments. So surface integrity must be taken into consideration and controlled.

A large number of researchers have attempted to
investigate the effects of process parameters on surface integrity in cylindrical grinding. The surface roughness is affected by process parameters such as wheel speed, feed, grinding depth and workpiece speed [4, 5]. The spark-out stage has an important role for reduction of surface roughness [6]. And the surface roughness under different cooling environment presented a wide variety [7, 8]. The amplitude of residual stresses after grinding is usually influenced by heat treatment method and grinding parameters [9, 10]. Moreover, with the correct selection of grinding conditions, the very favourable compressive residual stresses in the hardened surface layer on main bearing will be retained after grinding [11].

Although many works have been done, much attention has been paid to the cylindrical plunge grinding; few reports have been reported on surface integrity of pin bearing generated in path controlled grinding.

This objective of this paper is to design the grinding process parameters by investigating the surface integrity in path controlled grinding. A series of experiments has been carried out to investigate variation in terms of surface roughness and residual stresses along circumference of crankpin which influence the reliability of components. In addition, analyses on speed of crankpin and wheel were also investigated. This paper provides a well fundamental understanding the path controlled grinding process of crankpin.

2. Experimental procedures

2.1. Specimen preparation

The material used in experiments was commercial 40Cr alloy. It is the reason for choosing 40Cr that it is used typically for ship crankshaft manufacturing. The main chemical composition of 40Cr is shown in Table 1. The pin bearing had the dimensions of 80 mm (diameter) ×35 mm (width), and the eccentricity is 67.5 mm. Quenched hardening and induction surface hardening according to the GB (Chinese standard) were used gaining the surface hardness of HRC 52±3.

Table 1 Chemical composition of 40Cr.

<table>
<thead>
<tr>
<th>C%</th>
<th>Si%</th>
<th>Mn%</th>
<th>S%</th>
<th>Cr%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.42</td>
<td>0.29</td>
<td>0.7</td>
<td>0.01</td>
<td>0.98</td>
</tr>
</tbody>
</table>

2.2. Experimental Setup

The grinding experimental platform used for path controlled grinding of the pin bearing grinding is shown in Fig. 1. All grinding tasks were carried out on an orbital grinder H-405BF supplying a spindle with maximum speed of 6000 rpm and drive motor rated up to 37 kW. The nozzle setup of coolant keeps a settled position. Cubic boron nitride (CBN) grinding wheels have been widely used in industries as an effective precision grinding method, and often they produced very good results [12]. The CBN grinding wheel with diameter of 600 mm and width of 38 mm with grit sizes 126 (KREBS&RIEDEL Inc. Germany) was used throughout experiments. Before each grinding test, the wheel was dressed with same parameter using diamond roller dresser with diameter of 150 mm (KUNTZ Inc. Germany). The grinding has been applied under flood emulsion cooling for each test and hydraulic pressure was set to 0.39 MPa. A water-based coolant was used in these tests with dilution ratios 1:15. The grinding conditions and dressing conditions are given in Table 2. Each test there is ten revolutions during loaded grinding and spark-out grinding.

Table 2 Experimental conditions

<table>
<thead>
<tr>
<th>wheel &amp; dresser</th>
<th>CBN(q600)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel speed $V_s$ (m/s)</td>
<td>75,80,85,90</td>
</tr>
<tr>
<td>Grinding depth $a_p$ (mm)</td>
<td>0.005, 0.01, 0.015</td>
</tr>
<tr>
<td>Rotation speed $V_w$ (rpm)</td>
<td>15,25,30,35,50</td>
</tr>
<tr>
<td>Dresser</td>
<td>Diamond roller dresser (q115)</td>
</tr>
<tr>
<td>Wheel speed (m/s)</td>
<td>30</td>
</tr>
<tr>
<td>Dressing speed (m/s)</td>
<td>24</td>
</tr>
<tr>
<td>Dressing depth (mm)</td>
<td>0.003</td>
</tr>
<tr>
<td>Dressing feed (mm/min)</td>
<td>200</td>
</tr>
</tbody>
</table>

2.3. Measurements

The measurement started from the rotation angle 0°. Twelve measurement points were taken along the grinding direction with separation angle of 30°. The measurements of surface roughness $R_a$ were taken on a surface roughness meter Mitutoyo SJ-201(Japan) across grinding direction. The cut-off used was 0.25 mm. An average of five readings of roughness was recorded. The X-ray diffraction technique using sin2ψ method was used. A Proto-iXRD X-ray diffractometer equipment (Canada) was used for the residual stresses measurements. The radiation power supply was 20kV and 4mA, and the radiation source used is Cr_K for canning in the 2θ range of 156.41°

3. Analysis of Path Controlled Grinding of Crankpin

For path controlled grinding, the crankshaft is held between head stock and tailstock centres in these tests, the crankpin is eccentrically ground with an angular infed grinding process. To well understand the process during crankpin path controlled grinding, the speed and grinding ratio are investigated. It is assumed that the rotation speed of crankshaft is constant in this analysis. It is assumed that the
rotation angle $\phi$ is zero when $O_1O_3$ coincides with the positive $x$ axis in Fig. 2. The resultant pin bearing speed and wheel speed are given with respect to the main axis rotation angle $\phi$ as:

$$\beta = \arcsin \frac{R_s \sin \phi}{R_p + R_s}$$  \hspace{1cm} (1)

$$\delta = \arctan \frac{R_s \sin \beta}{R_p \cos \phi + R_s \cos \beta}$$  \hspace{1cm} (2)

$$O_P = \sqrt{[R_p \cos \phi + R_s \cos \beta]^2 + (R_s \sin \beta)^2}$$  \hspace{1cm} (3)

$$V_{\text{sw}}(\phi) = \omega O_P \cos (\delta + \beta)$$  \hspace{1cm} (4)

$$V_s(\phi) = V_s \sin \beta + V_i$$  \hspace{1cm} (5)

Where $\phi$ is rotation angle, $R_o$ is the eccentricity of crankpin, $R_s$ is wheel radius, $R_p$ is the radius of pin bearing, $V_{\text{sw}}$ is the tangential crankpin speed along $U$ axis, $V_s$ is the tangential wheel speed along $V$ axis, $\omega$ is the angular speed of crankshaft, $V_i$ is the substantial wheel speed.

The speed characteristics of grinding point on crankpin and wheel, grinding ratio were plotted as a function of rotation angle of crankshaft when $R_p=40$ mm, $R_o=67.5$ mm, $R_s=300$ mm, $V_i=90$ m/s, $V_s=35$ rpm, $a_p=0.01$ mm in Fig. 2. It is seen that the variation of speed for wheel and pin bearing can be divided into two modes during one revolution cycle. During the first mode, the directions between wheel and workpiece speed are opposite, thus this stage means up grinding. When the directions between wheel and workpiece speed are same, this mode is called down grinding. The grinding mode occurred along the circumference of crankpin alternating between up grinding and down grinding.

4. Results and discussion

4.1. The result and analysis of surface roughness

Fig. 4 shows the measured surface roughness (Ra) of the ground workpiece in each experimental test. The values given in Fig. 4 are the averages of five measurements from the surface profilometer. The values of roughness fluctuate corresponding to the rotation angle within each grinding test respectively.

The results show that the values of roughness are not same along the circumference of pin bearing. As above discussed, the varied grinding condition leads to the fluctuation. It is noted that the values of roughness is lower during down grinding. The surface roughness values Ra keep below 0.252 $\mu$m under each grinding condition respectively. It can be seen that the surface roughness values at the surface area are appreciably smaller. The maximum difference between maximum roughness and minimum roughness is 0.05 $\mu$m for
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Fig. 4 Variation of surface roughness

given grinding tests. This highlights the fact that the good quality surfaces can be produced at the whole circumference with the enough spark-out grinding under varied variation grinding conditions.

As for variation of crankshaft rotation speed and grinding depth, these conclusions are not partially consistent with the result of grinding reported by other authors [5, 13]. The surface roughness increases when crankshaft rotation speed increases from 15 rpm to 35 rpm and decreases when the crankshaft rotation speed is increased from 35 rpm to 50 rpm. Moreover, it is observed that surface roughness decrease with the increase of grinding depth, although the increase in material removal rate and chip thickness with the increase of grinding depth. It can be seen from Fig. 4 that the variation process of surface roughness with varied grinding depth is much more stable than those of other cases with rotation speed 25rpm. The authors consider that this phenomenon is derived from the influence of grinding conditions between the grinder and the circular specimen. From discussed earlier, it can be obtained that it is a non-uniform accelerating process for the movement of grinding point with impact. The lower rotation speed of crankshaft results in stable grinding conditions.

Down grinding and up grinding exist in one cycle. Pei-LumTso reported that the surface roughness is different with same grinding parameters in down grinding and up grinding [14]. Additionally, the nozzle setup of coolant keeps a settled position. It leads to variation of coolant condition which could cause a variation in surface roughness normally [7]. It is known that the forces applied to crankshaft are unsteady [15]. Material removal in grinding produces by microcutting action of abrasive grits. Due to the function-related mechanical structure of crankshaft, the workpiece stiffness have an actively influence on the grinding process [1]. However, each test there is ten revolutions during loaded grinding and spark-out grinding. Finally, the surface roughness can be obtained by the combined effect of multiple parameters during path controlled grinding.

4.2. The result and analysis of surface residual stresses

It can be seen that the compressive residual stresses obtained on pin bearing after path controlled grinding in both heat treatment methods as shown in Fig. 5. Fig. 5(a) shows the result after grinding using quenched hardening. Fig. 5(b) and (c) shows the result after grinding using induction surface hardening. The profiles of surface residual stresses do not show well-defined tendencies as depicted in Figs. 5(a), (b) and (c). The difference of maximum and minimum residual stresses is 58.9 MPa, 51.8 MPa, 73.2 MPa, 52.5 MPa, 65.1 MPa, 87.4 MPa, 70.8 MPa, 47.8 MPa and 66.8 MPa in these tests respectively.

This result reveals that residual stresses after path controlled grinding are relatively high levels of compressive nature in the induction surface layer. The peak compressive residual stress using induction surface hardening is about 736.7 MPa higher than the peak compressive residual stress 491.5 MPa using quenched hardening as shown in Fig. 5. The residual stresses level using different heat treatment methods shows the same result presented by previous studies [10, 11]. The compressive residual stress using induction surface hardening is high than that using quenched hardening. The cause of residual stress in grinding has three mainly aspects: mechanical deformation, thermally-induced plastic deformation and phase transformations [16]. These residual stress produced by mechanical interactions of abrasive grains with the workpiece is believed to be compressive. Tensile stress is caused mainly by thermally induced stresses and deformation associated with the grinding temperature. The final residual stress is determined by the combination of thermal and mechanical mechanism.

To evaluate the effect of grinding parameter to residual stress, the residual stress of pin bearing using quenched
Fig. 5 Variation of surface residual stress

hardening was measured before grinding. It is -252.9 MPa parallel to the grinding direction and -90.7 MPa perpendicular to the grinding direction. The residual stress is -412.4 MPa parallel to the grinding direction and -68.9 MPa perpendicular to the grinding direction when $V_s=75$ m/s, $V_w=30$ rpm, $a_p=0.01$ mm. It can be seen that the residual stress values are appreciably bigger than that before grinding. Surface layer material of workpiece that parallel to the grinding direction has been stretched, but the material that perpendicular to the grinding direction has been compressed. As a result, it leads to the increase of compressive residual stress in the direction that parallel to the grinding direction, but tensile residual stress in the direction that perpendicular to the grinding direction.

No grinding burn marks are found on the surface of the crankpin. Because of good thermal conductivity, CBN abrasives take away more energy from the grinding zone. Heat is regarded as the important resource leading to tensile residual and mechanical deformation results in compressive stress. Due to the increase of compressive residual after grinding, the fact for all obtained results highlights the preponderance of mechanical over thermal effects.

4. Conclusions

An investigation was conducted to observe the circumferential distribution of surface roughness and surface residual stress with different grinding parameters during path controlled grinding of crankpin. Complex grinding conditions present during one revolution of crankshaft. The grinding mode alternates between up-grinding and down-grinding along the circumference of crankpin during one revolution. High-quality surface was obtained from the investigated grinding conditions. The circumferential surface roughness with very little difference is obtained, despite the varied grinding conditions. High compressive residual stresses can be remained after path controlled grinding. However, compared to the results after grinding, induction surface hardening offers higher compressive residual stress. Moreover, unlike the circumferential distribution of surface roughness, the influence of varied grinding conditions could not be omitted on circumferential distribution of surface residual stresses.

The results in this study could provide an insight into the understanding of surface roughness and residual stresses distribution induced by path controlled grinding. Based on the experimental results and speed analysis of crankpin and wheel, the variation of surface roughness and residual stresses on circumference of crankpin could be controlled by the grinding parameters. It is suggested that the lower crankshaft rotational speed, lower grinding depth, and higher wheel speed can be used in the path controlled grinding of crankpin harden by induction surface hardening.

Our future work will focus on the relationship of temperature, hardness and the dressing parameters on the roughness and residual stress.

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