Experimental Study of Gear Bending Fatigue Strength with Pulsed Electron Beam after grinding tooth surface

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Abstract: The gear was deal with electron beam, and microhardness, roughness, topography and organization structure and stress on gear surface were measure and their effect to gear bending fatigue strength was analyzed and discussed. Experimental of gear bending fatigue strength was accomplished and contrasted before and after they were dealt with pulsed electron beam after grinding tooth surface. The surface hardness of 40Cr can be changed within in 2 mm under the surface. For grinding gear which was treated by electron beam, tooth surface roughness has a certain degree of enhancement. Because electron beam has the polishing effect, so many small scratches on the root surface of the grinding gear have disappeared, and the grain size in the material’s surface has been refined. The results demonstrated that gear bending fatigue strength after irradiation was improved 6.1% than that before irradiation at the condition of reliability 50%.

Keywords: tooth surface; Pulsed Electron Beam; Bending Fatigue; Experimental Study

1 Introduction

As main driving part, gear was most import component in mechanized equipment because of its advantages, which included accurate transmission ratio, reliable motion, high efficiency, compact structure and mature technology for producing. So gear possesses irreplaceable situation especially in greater dynamic occasion, such as large-scale generating equipment, cement machinery, synthetic ammonia equipments, rolling machine and warship, and so on [1].

The destructive forms were various because stress of gear was complicated in work. The common severe destroy include snaggletooth, scuffing and pitting corrosion, among which fatigue bending break of gear is a serious destroy [2]. Conventional methods to improve bending fatigue strength include shot blast and extrusion process. But these processing could not improve contact fatigue strength of gear. So additional surface strengthening should be adopted such as carburizing, nitriding, carbonitriding, laser surface strengthening and thermal spraying [3].

In recent years, material surface modification technology was developed largely with pulsed electron beam irradiation [1, 2]. This surface modification technology could improve material wear resistance and corrosion resistance, and it can increase material microhardness in 1mm. The stress because electron beam impact can hinder dislocation motion and delay crack growth, which maybe improve gear bending fatigue strength. Here experimental was accomplished to study gear bending fatigue strength with pulsed electron beam after grinding tooth surface.

2 Experimental schemes

2.1 Parameters and Material of testing gear

The parameters of testing gear were selected according to GB/T14230-93(Standard of test method for bending load capacity of gears). The tooth shape was involute and module m was 3mm. Tooth width b was 12mm. Pressure angle a on pitch circle was 20°. Spiral Angle β was 0°. Coefficient of profile displacement x was 0. Tooth height h was 1.25m. Tooth root fillet p0 was 0.3m. The tooth surface was grinded.

Material was 40Cr(C0.40,Si0.23,Mn0.7,Cr0.8,Ni≤0.30-wt%) commonly used in gear industry. Gear billet forgings ob≥950MPa, While carburized and quenched gear DC≈1.5–1.75. Hardness was 45–50HRC at gear surface, and hardness was 30–42HRC at the core.

2.2 Test platform of electron beam

The gear surface was irradiated with electron beam on RITM-2M, which was made by Russia. It had the

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operating parameters as follows: electron energy 10-40keV, pulse duration 5-10 ms, peak current density 1-6Jcm-2 and cross-section area 30cm2.

2.3 Organization and performance testing of gear

Vickers hardness was measured on root and waist of gear with microhardness measuring instrument (HX-1000) . Surface roughness of tooth root was measured with roughmeter TR-200. Section organization was observed on scanning electron microscope JSM-6460LV. The residual stress gear was measured on root with X-ray diffractometer.

2.4 Bending fatigue strength experiment

Combination method was adopted to determine bending fatigue S-N curve with less experimental point according to GB/T 14230-93. That was, the 7 or 8 stress level was selected, while every stress level included 1 test point. The fatigue test was carried out on PLG-200 High-frequency fatigue tester under constant load in order to improve test efficiency[4].

3 Results and discussion

3.1 Microhardness

Microhardness was shown in Fig.1 (a) on tooth surface. As can be seen, microhardness ascend a little firstly and then descend by a large margin, finally flatten out before and after electron beam irradiation, which was core hardness. The hardness was decreased in teeth root under 2mm surface and maximal decreasing amplitude exceed 100HV after electron beam irradiation, which was arose by low temperature annealing because of multiple electron beam irradiation. Electron beam deal with material in dual function, which include energy and impact. Energy could cause material annealing, which reduced material hardness. Impact could cause dislocation changing, which enhanced material hardness. The material annealing was dominant in gear root with electron beam irradiation.

In contrast, as was shown in Fig.1(b), the hardness was increased to some degree in teeth surface under 1.2mm surface after electron beam irradiation. That was because impact function was greater than annealing function. That was that material impact was dominant in gear surface with electron beam irradiation.

The average hardness was increased 3.7% in teeth surface, while it was decreased 21.9% in teeth root. The difference in teeth root and teeth surface was caused by gear special shape. On the one hand, the teeth volume was less relative to gear body so the heat storage capacity was less as well. On the other hand, the direction of electron beam differed because of difference in magnetic line direction, so energy was different in tooth surface and root.

![Microhardness of gear](image)

(a) hardness of teeth root  
(b) hardness of teeth surface

Fig.1 The microhardness of gear

3.2 Surface roughness

The roughness contrast before and after irradiation were shown in Fig.2. The roughness increase mainly was induced by plentiful crater in gear surface, which was produced because of electron beam irradiation, as was shown in Fig.3. Firstly when electron beam energy was irradiated on material surface, most energy deposition was located in. So material melt firstly in subsurface, then material volume increased, which cause local droplet
unstability and spurting. Then crater was keep down because of basal body quick cooling and come into being defects like fire pit[3]. The roughness was influenced by two aspects, crater coming into being and microprotrusions filling and level up. Here crater coming into being was dominant in gear root with electron beam irradiation.

![Graph showing roughness before and after irradiation](image)

**Fig.2 roughness contrast before and after irradiation**

**3.3 surface topography and organization structure**

Surface topography before and after electron beam irradiation could be shown in Fig.4. It could be seen that electron beam play a part in polishing although roughness increase in teeth root. So many polishing scratch can be observed in teeth root in Fig.4 (a) clearly after grinding tooth surface. But sharp polishing scratch flatten and even was eliminate, so surface condition improved well to a certain extent, as was shown in Fig.4(b).

![Surface topography in teeth root](image)

**Fig.4 Surface topography in teeth root**

Cross-sectional SEM microphotograph after electron beam irradiation was shown in Fig.5. Surface layer had greater difference with deep layer body, as was point with arrow. A mass of energy was deposited on material surface in a short time when pulsed electron beam was used, so that temperature of heated floor increased rapidly and material surface was melted. So second-phase diffused and material recrystallized quickly, then fine grain structure came into being in surface layer. This fine grain structure was retained because surface layer was cool down by basal body [6]. Finally grain was refined in surface layer and massive carbonizations disappear contrasted with basal body.

![Cross-sectional SEM microphotograph after irradiation](image)

**Fig.5 Cross-sectional SEM microphotograph after irradiation**

**3.4 Stress tests on gear surface**
The residual stress of original samples was 472MPa by testing in teeth root surface, while that was 635MPa after electron beam irradiation, which all were tensile stress. The tensile stress of original samples was produced in grinding process.[7] When irradiated with electron beam, the material surface was smelt, so the original residual stress was eliminated, and then the new residual stress appeared with cooling of metal. On the basis of study, it will generate some austenite in 40Cr when remelting after being irradiated with electron beam. Austenite generation should produce greater tensile stress because austenite possesses lesser specific volume in various steel organizations.[8]

3.5 Bending fatigue experiment

The S-N curve were placed under two conditions in the same coordinate system to compare, as showed in Fig.6. It showed that fatigue life before irradiation was improved 6.1% than that before irradiation. So many factors influence bending fatigue strength of gear to a greater degree, which mainly include microhardness, roughness, topography and organization structure and stress on gear surface. ① The microhardness descend a little in teeth root after electron beam irradiation, which would make bending fatigue strength descend a little as well. ② As for roughness, it increased in teeth root. But electron beam polished teeth root and surface. So the stress concentration caused by polishing scratch was decreased accordingly, which would increase bending fatigue strength of gear. ③ Grain was refined in surface layer and massive carbonizations disappear contrasted with basal body. So the surface organization was improved greatly. That would restrain crack generating and growth, which ought to make a greater contribution to bending fatigue strength of gear. ④ The residual stress was increased in teeth root after electron beam irradiation, which would give rise to crack generating. But residual compressive stress exists in material subsurface with electron beam irradiation in great depth. That help to close crack thus restrain crack growth. So residual compressive stress in subsurface counteract partial effect caused by residual tensile stress in surface [9]. The structure property work changes in teeth surface and root when gear was deal with electron beam. These changes play functions in gear bending fatigue strength. In general these functions were positive so the gear bending fatigue strength was increased.

![Fig.6 Comparison of test result(R=0.5)](image)

4 Conclusions

Experimental of gear bending fatigue strength was accomplished and contrasted with pulsed electron beam after grinding tooth surface. The results was contrasted and discussed in several ways, which include microhardness, roughness, topography and organization structure and stress on gear surface. So conclusion could be as follows:

(1) The average hardness was decreased to a certain extent in teeth root under 2mm depth, while The average hardness was increased a little in teeth root under 1.2mm depth

(2) Roughness was increased in teeth root. But electron beam polished teeth root and surface. Polishing scratch was eliminated in teeth root when gear was irradiated with electron beam. And Grain was refined in surface layer and massive carbonizations disappear contrasted with basal body. So the surface organization was improved greatly.
(3) The residual stress was increased in teeth root after electron beam irradiation. But residual compressive stress in subsurface restrain crack growth.

(4) At the condition of reliability 50%, Gear bending fatigue strength after irradiation was improved 6.1% than that before irradiation.

Acknowledgements

The work has been supported by National Natural Science Foundation of China(51275548), Chongqing science and technology commission((cstc2012jjB0002 and cstc2012gg-yyjs70019) and Innovation team of Chongqing Education Commission.

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