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Effect of shot peening on the fatigue resistance of laser surface melted 20CrMnTi steel gear

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ABSTRACT

The effect of combined laser surface melting and shot peening (LSMSP for short) on fatigue resistance of 20CrMnTi steel gear is investigated in this paper. After laser surface melting (LSM) treatment to gear tooth flanks, gear was treated by shot peening (SP) with different peening intensities. The residual stresses, full width at half maximum (FWHM), microhardness, retained austenite volume fraction and surface roughness of the LSMSP gear were measured. The Forschungsstelle für Zahnräder und Getriebebau (FZG) back-to-back spur gear test rig was used for fatigue experiments. Experimental results showed that compressive residual stress in the LSMSP gear tooth firstly increased to a maximum value and then decreased to stress state of the substrate. With improving strength of shot peened specimen, maximum values and depths of compressive residual stresses increased in the LSMSP gear. Owing to grain refinement, FWHM of the LSMSP gear tooth was broadened obviously along the direction of depth. Through LSMSP treatment, the retained austenite volume fraction of the LSMSP gear was lower than 5% in the LSMSP surface layer. The microhardness of the LSMSP gear tooth has been raised above 20%. The fatigue and wear resistance of the LSMSP gear was much better than that of the LSM and SP gears.

1. Introduction

With heavy-duty and high-speed development trends of the automotive industry, there are growing requirements for reliability of automotive gears. How to extend the service life of gears has become a problem to be resolved. The service life of gears is associated with their fatigue and wear performance. The main factors that affect the fatigue strength of gears include residual stress, volume fraction of retained austenite, surface roughness and microhardness. Residual stress is the most important for the fatigue resistance of gears among all of the factors. There are many cold and thermal treatments for gears. Every treatment could induce different depths and values of residual stresses into the surface layer of gear teeth. The fatigue resistance mechanism of gears is that fatigue resistance of gears improves with an increase in compressive residual stresses in gear teeth. In industrial processes, the processing technologies that induce residual stresses into gear include high frequency quenching, carburizing, nitriding, carbonnitriding, shot peening [1,2], deep rolling, grinding, laser surface modification [3] and combined strengthening treatment. The various treatments differ in values and depths of residual stresses, which limit their use areas. In addition, strengthening effects of treatments change with different types of materials.

Laser surface melting (LSM) is used to heat and melt the local region of the metal surface at a high laser power density, and then the melted surface layer is rapidly solidified by means of endothermic reactions of substrate and heat conduction. The microstructure of the remelted layer is casting structure, and has high microhardness. Laser surface melting treatment has been used to improve the wear [4–6] and corrosion [7,8] resistance of many kinds of irons and steels, such as magnesium alloy [9,10], aluminum alloy [11], tool steel [12–14], medium carbon steel [15]and stainless steel [16,17]. However, tensile stresses exist in the surface layer of laser-melted components and parts, which are detrimental for the wear and corrosion performance of materials. This problem must be solved as soon as possible.

Shot peening (SP) is a simple and effective means to improve the fatigue strength of a wide variety of metallic or nonmetallic materials [18–22]. The mechanism of shot peening is that the quickly flying shot shocks the surface of material, and then the uneven plastic deformation is generated in the surface layer. Meanwhile compressive residual stress fields would be induced into the materials. Shot peening treatment can enhance mechanical reliability and prolong the service life of workpieces, such as gears [23], bearings and blades.

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In this paper, the effect of shot peening on fatigue performance of laser surface melted 20CrMnTi steel gear would be investigated. After laser surface melting (LSM) treatment to gear tooth flanks, gear was treated by shot peening (SP) with different peening intensities. The residual stresses, FWHM, microhardness, volume fraction of retained austenite and surface roughness of the LSMSP gear were measured. The FZG test rig was used for fatigue experiments. The combined laser surface melting and shot peening (LSMSP) treatment can be applied to productive practice in the future.

2. Experiment details

2.1. Gear material and LSM treatment

The chemical composition of 20CrMnTi steel is listed in Table 1. Laser surface melted treatment were carried out using a 4.5 kW Nd:YAG pulsed laser with a wavelength of 1064 nm, laser energy densities of 35 MJ/m^2, a laser beam diameter of 1 mm, a frequency of 8 Hz, a laser scanning speed of 1 mm s^{-1}, a duration time of 10 ms and argon flowing at 20 l min^{-1} using as shielding gas. The laser-melted processing was executed by a computer numerical control program. The overlapping ratio of the successive melted tracks was 50%. The LSM teeth were sectioned, polished and etched with a solution of alcohol and nitric acid. The microstructure of the melted zone was observed by a scanning electron microscopy (Model JSM-6490LV, Japan).

Fig. 1(a) shows that the microstructure of 20CrMnTi steel is composed of ferrite and lamellar pearlite. Owing to high temperature and fast cooling rate, four regions were formed in the laser surface melting layer, namely melted zone (MZ), transition zone (TZ), heat affected zone (HAZ) and substrate, shown in Fig. 1(b). Fig. 1(c) shows the microstructure of the MZ. Laser beam irradiated gear tooth flank directly. Temperature of the MZ was above Ac3. Composition distribution of 20CrMnTi steel was relatively uniform, and thus carbon and alloy elements fully diffused, and the homogeneous retained austenite was obtained. During fast cooling, needle-like martensite, some of autenite and carbide were generated in the direction of the most temperature gradient. Fig. 1(d) shows that the MZ is composed of phases as ferrite (α), martensite, carbide and retained austenite (γ). The X-ray diffraction profile was also in consonance with the microstructure of the MZ.

2.2. Shot peening

Shot peening treatment was completed by a pneumatic numerical control shot peening machine. The angle of shot peening was set through a four-axis robotic arm. The direction of shot peening was manipulated by a four-axis automatic control system to ensure that the best result of shot peening would be obtained for gear. The LSM gears were treated by shot peening with different peening intensities (from 0.3 MPa to 0.5 MPa). All the shots had been cut by wire-steel. The cast steel shot was made to have a diameter of 0.6mm and hardness of 60HRC. The diameter of peening nozzle was 20 mm. The distance between peening nozzle and gear tooth flank was 90 mm. Almen A type strips were used to measure peening intensities. Table 2 shows the shot peening parameters for the LSM gears in detail. A group of untreated gears had been treated by shot peening with a peening intensity of 0.40 Mpa, called “SP gear”.

Table 1
Chemical composition of 20CrMnTi steel.

Element	Composition (Wt%)
C	0.17–0.23
Si	1.00–1.30
Cr	0.17–0.37
Mn	0.80–1.10
Ti	0.04–0.10
S	$\leq$ 0.035
P	$\leq$ 0.035
Cu	$\leq$ 0.025
Fe	Balance

2.3. Surface roughness measurement

The roughness of the LSM gears was measured by Veeco Wyko NT1100 optical profiler using the arithmetic average roughness R_a. The roughness of every gear tooth was measured 5 times, and average surface roughness can be obtained.

2.4. Residual stress measurement

Residual stresses were measured by XRD on the (211) interference line of the LSM gear tooth flank using Cr Kα radiation. The measured interference peaks were evaluated according to the $\sin^2 \psi$ method and angle of ψ was varied every 10° in the range from $-70°$ to $+70°$. The depth profiles of the residual stresses were determined by iterative electrolytic removal of thin surface layers and subsequent X-ray measurement.

2.5. Retained austenite measurement

With the help of an X-350A X-ray diffraction tester and electrochemical stripping technologies, volume fraction of retained austenite and distribution on the LSMSP gear tooth flank were measured using Cr Kα radiation at an operating voltage of 25 kV with a current of 5 mA. Through the analysis of α(211) and γ (220), the volume fraction of retained austenite in a gear tooth was obtained in accordance with the GB8362-87 standard.

2.6. Microhardness measurement

Microhardness along the depth of the cross-section of gear teeth was measured by a Vickers hardness tester by applying 500 g load with dwell time of 15 s. The microhardness was average value of microhardness of 5 points at the same depth of teeth.

2.7. Fatigue tests of gears

The fatigue tests were carried out by using FZG machine, as shown in Fig. 2 [24]. The geometric parameters of test gears are presented in Table 3 and the test conditions are shown in Table 4. The properties of oil samples are given in Table 5. The gears in the tests were placed in an oil bath for lubrication at fixed 90 °C. For the LSM and LSMSP gears, after gear running 2.0×10^6 cycles, gearbox would be opened, the photographs of gear tooth flanks were being taken at 5 min intervals without dismounting gears, and then the pitting area of gear tooth could be measured, and finally the pitting rate of gear tooth could be obtained. For the untreated gear, after gear running 6.0×10^5 cycles, the photographs of gear tooth flanks were being taken at 5 min intervals, and the pitting rate of gear tooth could be obtained. According to the gear contact fatigue strength test standard “GB/T 14229-93”, each pair of gears was operated until its single pitting ratio reached 5%. The number of cycles of gear pair was the fatigue life of gears.