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Evaluating the fatigue cracking risk of surface strengthened 50CrMnMoVNb spring steel with abnormal life time distribution

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ABSTRACT

Surface strengthening is an important method which can effectively improve the fatigue property of metallic materials. In order to improve the fatigue property, for the first time, a new developed surface spinning strengthening-*II* (*3S-II*) method and the traditional shot peening (*SP*) treatment were applied to modify the microstructure and fatigue performance in the surface layer of 50CrMnMoVNb spring steel. It is interesting to find that the fatigue lives of the samples treated by the *3S-II* method show obvious polarization characteristics (either quite higher or slightly lower than those treated by *SP* method) at the high stress amplitude, which does not follow the traditional life distribution rules and cannot be evaluated by the *S-N* curve. Moreover, the fatigue lives of the samples with the fatigue crack initiated from the surface defects are extremely lower than those of the samples whose fatigue crack initiated from the subsurface. Therefore, a fatigue risk factor, "R_f", was proposed and developed based on the competition between the applied stress and the material property to evaluate the fatigue cracking risk of the surface strengthened 50CrMnMoVNb spring steel, especially the fatigue risk of the samples influenced by the mixed factors. The calculation results show that the position where $R_{f\ max}$ appears is exactly the position of fatigue crack initiation. As a result, "R_f" can be used to quantitatively evaluate the fatigue risk of metallic material under the influence of a variety of factors, including surface strengthening, surface roughness and residual compressive stress and so on.

1. Introduction

Since environmental protection is a widely focused topic, lightweight has become an inevitable trend for the development of commercial vehicles, and the lightweight of key components is of great concern to achieve this goal [1]. Leaf spring is an important component whose main functions are vibration attenuation and load bearing [2]. Thus, fatigue is the most common failure mode for the leaf spring. For some commercial vehicles, lightweight commonly means to reduce weight, which may be potentially harmful to the fatigue reliability of the key components, e.g., leaf spring. Lightweight means that much more energy should be stored in the single leaf spring during the elastic deformation, resulting in a greater strain. In service, the maximum stress on the less leaf spring will also increase accordingly as compared with multi-leaf spring. As a result, lightweight and fatigue reliability constitute a contradiction to some extent. With the development of lightweight, ensuring the fatigue reliability of the key components has become a widely focused scientific issue that involves many aspects.

For most metals, strength and toughness are usually mutually exclusive, which makes the improvement of fatigue reliability a difficult problem for a long time. Surface strengthening, which can significantly suppress the crack initiation from the metal surface, is a good way to improve the fatigue reliability under the condition of lightweight [3,4]. As a common method of surface strengthening, mechanical surface strengthening can be divided into two categories based on the stress adopted, i.e., positive stress and shear stress. For the first category, positive stress is used for obtaining the deformation layer on the metal surface, e.g., shot peening (*SP*) [5,6], surface mechanical attrition treatment (*SMAT*) [7,8] and ultrasonic surface rolling processing (*USRP*) [9]; for the second category, shear stress is applied to the metal surface to induce the plastic deformation in the surface layer of metal, e.g., surface spinning strengthening (*3S*) [10,11]. In addition, rough surface caused by surface strengthening treatments has negative effects on the fatigue reliability [5]. Since surface roughness is also an important factor influencing the fatigue reliability and reducing the surface roughness is beneficial to decrease the stress concentration at the surface defects, which is helpful for improving the fatigue reliability of metallic components [12,13]. In general, mechanical surface

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strengthening contains a series of effective methods influencing the fatigue behavior of metallic components by controlling the microstructure in the surface layer as well as changing the stress distribution and the surface roughness [14–17]. In recent years, surface strengthening has already developed into an important subject which attracts wide attention, therefore, many researchers make great effects on revealing the fatigue mechanism of the surface strengthened metal and simultaneously explore better surface strengthening methods for improving the fatigue reliabilities of metallic components [18,19].

Surface spinning strengthening-*II* (*3S-II*) technology is a newly developed surface strengthening method based on the first generation technology (*3 S*) [10,11], which can effectively improve the surface strength of metallic components by a special designed machining tool, spiral roller. After the treatment, in the surface layer of metallic component, grains can be markedly refined even to a nano-scale and simultaneously introduce a large amount of dislocations and twins as well as a certain degree of residual compressive stress. It can thus significantly inhibit the fatigue crack initiation and improve the fatigue life of metallic components. In addition, the samples treated by *3S-II* can not only obtain considerable surface strengthening effects, but also significantly decrease the surface roughness. In this study, *3S-II* technology was applied to create a surface strengthening layer on the spring steel to improve the fatigue life of the spring steel.

After the surface strengthening, the position where fatigue crack initiates, the weakest point on the component, is the most concerned issue for researchers. For metallic materials, fatigue crack commonly initiates from either the surface or the center; however, the previous studies show that the fatigue properties of the identical metallic material are obviously different depending on the location where the fatigue crack initiates, i.e., surface or interior. Furthermore, even though metals were treated by *SP*, the position where fatigue crack initiates may not be the same, i.e., some on the surface and the other at the subsurface [20,21]. It is well known that there are many parameters influencing the position of fatigue crack initiation, such as applied stress, material performance, material defects, stress concentration and surface roughness and so on [21–23]. However, it is still a lack of a unified and comprehensive evaluation model to reveal the effect of material surface state, material properties and stress distribution on the fatigue risk of metallic components. Actually, the fatigue life time of metallic component is essentially the competition between the applied stress and the mechanical properties of materials.

In this study, the bending fatigue behaviors of the 50CrMnMoVNb spring steel treated by two different surface strengthening methods, *SP* and *3S-II*, were systematically investigated in order to reveal the fatigue cracking mechanism of the surface strengthened metal under the influence of mixed factors, such as surface state, strengthening layer and applied stress and so on. Finally, a unified model, fatigue risk factor (R_f) model, was proposed and developed to evaluate the fatigue risk of 50CrMnMoVNb spring steel.

2. Experimental procedures

2.1. Samples preparation

In this study, 50CrMnMoVNb spring steel, a typical Cr-Mn-Mo steel in the hot rolled state, was selected as the object material. 50CrMnMoVNb spring steel contains some micro-alloying elements, e.g. Nb and V, and is a common leaf spring material with excellent fatigue properties. The chemical compositions of 50CrMnMoVNb spring steel are listed in Table 1.

In this study, for the first time, the newly designed second-generation surface spinning strengthening (*3S-II*) method was developed to modify the surface layer of the 50CrMnMoVNb spring steel for the purpose of obtaining the surface strengthening layer and achieving a gradient microstructure with the gradient microhardness. Furthermore, the specially designed *3S-II* machine for the surface spinning strengthening treatment was used to prepare some samples with surface strengthening layer. The machining tool in the testing machine is a roller with spiral edge, which is schematically shown in Fig. 1. Not only low surface roughness which is closely related to the number, dimension and depth of spiral edge (Fig. 1(b)), but also better surface strengthening layer can be created by the *3S-II* method with shear stress (Fig. 1(c)). For the *3S-II* treatment, samples with dimensions of 150 mm × 90 mm × 28 mm were processed with the tool press amount of about 300 μm on the *3S-II* machine. In the following step, the samples with surface strengthening layer were cut into the metallographic samples (10 mm × 8 mm × 8 mm) and the bending fatigue samples (35 mm × 8 mm × 6 mm). By comparison, some samples treated by *SP* were also prepared by wire cut shots with diameter of 0.8 mm, because it was reported that *SP*, which must be used in the manufacture of leaf spring, can introduce residual compressive stress into the surface layer of leaf spring [24]. Surface morphology of 50CrMnMoVNb spring steel treated by different surface strengthening methods is shown in Fig. 2.

2.2. Microhardness and residual stress measurement

After the surface strengthening, microhardness in the surface layer of sample was tested in the direction of perpendicular to the surface on the cross section by a LECO AMH43 automatic hardness tester under the load of 300 g and the holding time of 13 s with a distance between any two adjacent indentations of 100 μm.

In addition, residual stress was tested using a proto-iXRD X-ray stress analyzer with the voltage of 20 kV and the tube current of 4 mA. Saturated NaCl aqueous electrolyte was used to corrode the metal from the surface to the inner layer at 700 μm by layer-by-layer electrochemical corrosion by a proto-8818 electrolytic polisher with the corrosion voltage of 15 V and the corrosion current of 2 A. Moreover, the depth of corrosion was measured using a digital micrometer.

2.3. Surface roughness measurement and microstructure characterization

The roughness of the meal surface was measured by a laser scanning confocal microscope (LSCM) under 20-fold objective lens to obtain the arithmetic average value (Ra) of the surface outline and the height of peak & valley arithmetic average value (Rz). For a single field, the sampling lengths (lr) of the samples treated by *3S-II* and *SP* method are 0.8 mm and 2.5 mm, respectively. Moreover, the total sampling length is 5 × lr. The average values of Ra and Rz from five different positions measured by LSCM were approximately considered as the surface roughness of sample.

The cross sections were cut from the samples treated by *3S-II* and *SP* for the microstructure characterization. The microstructure of cross section was characterized by a JSM-6510 scanning electron microscope (SEM), and the specimens were corroded by the solution of HNO_3:C_2H_5OH = 1:24. The subsurface (about 30 μm to the topmost surface) microstructure was observed by an FEI Tecnai F20

Table 1
Chemical compositions of 50CrMnMoVNb spring steel.

Element	C	Si	Mn	Cr	Mo	V
wt%	0.47–0.53	0.15–0.40	0.70–1.10	0.90–1.20	0.15–0.25	0.05–0.10
Element	Nb	Ni	Cu	P	S	Fe
wt%	0.02–0.05	≤ 0.35	≤ 0.25	≤ 0.020	≤ 0.015	Balance