PAPER

Improving the cycle fatigue life of spring steel by a novel thermal cycling process

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Abstract
A novel thermal cycling process was applied on the 65Mn spring to improve the cycle fatigue life. Results demonstrate that the cycle fatigue life after the thermal cycling process was improved from 3 times to 14 times, with an improvement of 470%. The fine, equiaxed grains were observed on the fracture surface. Moreover, the prolongation of cracks was prevented by the high density of interfaces, and the slipping and rotating between the grains consumed the applied energy during the cycling process, contributing to the improvement of cycle fatigue life.

1. Introduction

The spring fasteners are widely used in railway and automotive industries [1, 2]. Thus, the development of the high-speed passenger railways and the high-performance automobile highly depend on high-quality springs [3]. Since heat treatment is a vital process in fabricating springs, it is urgent to improve the mechanical properties of the spring [4, 5]. Ren et al [6] reported that the spring steel oil-quenched at 875 °C and tempered at 530 °C obtained excellent yield strength, ultimate tensile strength, and bending properties. Ramesh Kumar et al [7] improved the low cycle fatigue property of the spring steel by prolonging the heat treatment process. Chen et al [8] demonstrated that the change in solution temperature has little effect on the ductility of the spring steel while the high tempering temperature is beneficial to improve the ductility of the spring steel at room temperature. Pattnaik et al [9] developed a novel heat treatment process with a newly developed quenching setup for water quenching to improve tensile loading and interfacial shear strength. However, the improvement of cycle fatigue life, which is an essential performance for spring, through heat treatment is exiguous.

In this study, a novel thermal cycling process, which has been used to improve the bonding strength of steels, was applied on the spring steel to extend the cycle fatigue life [10, 11]. Besides, the effects of different heat treatment processes were investigated to clarify the mechanism of fracture. Evolution of the cycle fatigue life and microhardness were examined, and the fracture surfaces were observed. In this investigation, a new method for the heat treatment of spring was proposed, and it has been increasingly applied in railway and automotive industries.

2. Experimental

Commercial 65Mn spring steels (provided by China Iron & Steel Research Institute Group, with a diameter of 0.5 mm) were used as raw material. The microstructure was illustrated in figure S1 (available online at stacks.iop.org/MRX/8/056516/mmedia), and the chemical composition was listed in table S1. The steel wire presents a homogeneous microstructure of fine fibers with a width of a few microns. The homogeneous microstructure without gradient introduced by the manufacturing process is beneficial to the physical properties of the spring steel after heat treatment [6, 7].
A schematic diagram of the heat treatment processes was presented in figure 1. The straightened spring steels were heated using an SRJX-8-13A box-type annealing furnace. Firstly, the spring steels were quenched at 820 °C/1 h, marked as Sample 1. Then, Sample 1 was tempered at 350 °C/0.5 h and cooled in the furnace, marked as Sample 2. Finally, Sample 2 was quenched and annealed at 350 °C and 0.5 h, respectively. The quenched one and the annealed one were marked as Sample 4 and Sample 3, respectively.

The morphology of fracture surfaces was observed by a LEO1450 scanning electron microscopy (SEM). The microhardness was measured by a 430SVD Vickers Microhardness tester, with a load of 9.8 and hold time of 15 s. Then, the indentation was observed by an Imager, M2M optical microscope (OM). The cycle fatigue life was tested according to the 'ISO 7801:1984 Metallic materials; Wire; Reverse bend test' standard, as illustrated in figure S2. The cycle fatigue life test was conducted at room temperature. The spring steel was bent to 90°, followed by the other 90° bending in the contrary direction. This process was marked as one cycle. The cycles when fracture of the spring steel occurred were recorded to evaluate the cycle fatigue life of the spring steels. The cycle fatigue life and microhardness were examined five times, and the average value was applied.

3. Results and discussion

In figure 2(a), the cycle fatigue life of the spring steels before and after heat treatment processes is exhibited. The number of cycles to failure for the original spring is 3 times. After quenching, the number of cycles to failure is significantly reduced to 1 time in Sample 1, increased to 4 times in Sample 2 with the tempering process, improved to 5 times in Sample 3, and dramatically increased to 14 times in Sample 4 with the increase of 470% compared to the original one. It is reported that the ductile and bending strength of the spring steel could be influenced by the tempering temperature and duration. Raising the tempering temperature and prolonging the tempering duration are beneficial to homogenize the microstructure, contributing to the improvement of the comprehensive mechanical properties [7, 8]. Since the thermal cycling process could also have the effect of
prolonging the tempering duration, it may improve the homogenization of microstructure and increase the number of cycles to failure.

The inserted images indicate that the intender of the original spring is ‘sinked in’ type, and is transferred into ‘piled up’ in Sample 4 [12]. This phenomenon demonstrates that the string has been transferred from ‘strain hardening’ to ‘strain softening’, facilitating the followed deformation.

The microhardness of the springs is displayed in Figure 2(b). The microhardness is significantly improved to more than 900 HV in Sample 1 and then reduced to 370.2 HV in Sample 2 after tempered. Besides, the microhardness of Samples 3–4 is 335–345 HV, respectively.

The fracture surface of the original spring is exhibited in Figure 3(a). Region 1 is the initiation of the cracks, illustrating the morphology of brittle fractures. Then, the cracks tend to be parallel to the grain boundary (region 2). The intergranular fracture accompanied with some transgranular fractures happened along the cracks (region 3), and some grains are stripped (region 4).

The fracture surface of Sample 1 is presented in Figure 3(b), where the brittle fracture zone on the edge (region 5) and the ductile fracture zone in the center (region 6) can be observed. The brittle fracture zone is significantly larger than that of the ductile fracture zone. The fracture surface of Sample 2 is displayed in Figure 3(c), where the brittle fracture zone on the edge (region 7) and the ductile fracture zone in the center (region 8) can be observed. However, region 7 is much smaller than region 8, suggesting the improvement of ductility in Sample 2. Besides, the fracture surface of Sample 3 is exhibited in Figure 3(d). The fine dimples are uniformly distributed on the fracture surface, confirming excellent ductility. The fracture surface of Sample 4 is
presented in figure 3(e). It distributes equiaxed grains with some microns. Most of the fracture occurs along the boundaries of the grains, and some of the fracture crosses the grains.

The fracture mechanisms of the spring before and after the heat treatment processes are illustrated in figure 4. For Sample 1 and Sample 2, brittle fracture occurred on the edge, and ductile fracture occurred in the center of the spring. The strain energy of the edge is higher than that of the center, and the critical intensity factor of dislocation emission at the crack tip is affected by the strength and width of the brittle edge [13]. This structure could repulsive the dislocation [14]. Since the ductile fracture zone of Sample 2 is larger than that of Sample 1, it possesses a greater effect on the prevention of the prolongation of cracks, as shown by figures 4(a) and (b). For Sample 3, the ductile fracture zone is distributed on the whole fracture surface. Hence, the prevention effect of the cracks can be further improved, as exhibited in figure 4(c).

For Sample 4, the prolongation of cracks accompanied with branching, stretching, and bridging under the effect of fine, equiaxed grains [15]. Thus, the prolongation path of the cracks is extended by the diversified prolongation of the cracks, as illustrated in figure 4(d). The diversified prolongation of Sample 4 could be attributed to the fine, equiaxed grains. The high density of interfaces could prevent the prolongation of cracks in all directions [16, 17]. Although it is beneficial for slipping and rotating between the grains, it would slow down the prolongation speed of the cracks and thus improve cycle fatigue life [18–20].

4. Conclusions

In this study, a novel thermal cycling process was applied on the spring to improve the cycle fatigue life. Meanwhile, other heat treatment processes were investigated for comparison. The conclusions can be drawn as follows.

The microhardness of spring dramatically increased after quenched at 820 °C/1 h and decreased after tempered at 350 °C/0.5 h, followed by quenching at 350 °C/0.5 h. While the cycle fatigue life of spring after the thermal cycling process is improved from 3 times to 14 times, with an improvement of 470%. The fracture surfaces of the samples quenched at 820 °C/1 h (Sample 1), followed by tempering at 350 °C/0.5 h. Sample 2 contains a brittle fracture zone on the edge and a ductile fracture zone in the center. The prolongation path of the cracks is unitary. The fine, equiaxed grains could be obtained on the fracture surface of Sample 2 after quenched at 350 °C/0.5 h. The high density of interfaces could prevent the prolongation of cracks, and the slipping and rotating between the grains could consume the applied energy during the cycling process, contributing to the improvement of cycle fatigue life.
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The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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