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TECHNICAL ARTICLE—PEER-REVIEWED

Failure Analysis of an Automobile Coil Spring in High-Stress State

Shuaijiang Yan · Qingxiang Wang · Xing Chen · Chengsong Zhang · Guodong Cui

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Abstract The present work details a study for the determination of causes of a prematurely failed automobile spring. Several tools consisting of visual observation, optical microscope, scanning electron microscope (SEM), energy-dispersive spectrometer (EDS) analysis, etc., were used on the failed product to investigate the underlying causes. Photographs of the failed spring showed large wear marks and machinery indentations on the surface. These wear marks indicated an improper installation which could cause additional stresses under service loads. SEM images of one of the indentations showed radiating ridges emanating from the indentation tip which indicated that it served as the fatigue initiation. EDS results showed foreign elements in the fatigue origin implying the existence of microcracks. Under the effect of service and additional load, a stress concentration point was formed and fatigue crack originated from the indentation tip resulting in the final rupture.

Keywords Automobile spring · Crack initiation · High-level stress · Fatigue striations · Fatigue failure

S. Yan · X. Chen · C. Zhang · G. Cui (✉)
School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu 610031, China
e-mail: gdcui@swjtu.edu.cn

Q. Wang (✉)
Sino-Euro Materials Technologies of Xi'an Co., Ltd., Xi'an 710018, China
e-mail: wangqx1981@163.com

Introduction

Coil springs are widely used in auto vehicle industry as one of the dominating members for connecting components. Due to the excellent elasticity and ductility, they are frequently used to connect wheels and the vehicle body to absorb shocks received from road irregularities that transmitted to the body [1]. Coil springs could also be used in the engine piston or the motor car clutch to control the movement of relative systems. Other applications such as helping bear the heavy weight of the car body, reducing vehicle weight, and smoothing out impact of adjacent parts are also indispensable for the auto industry.

Trends in auto industry aim at coil springs that could support lager loads and serve for a longer period. Most coil springs fracture because of fatigue, but there are different types of failure reasons. Raw material quality and spring surface status are two main factors that are related to the fatigue life of coil springs [2]. Microcracks and inclusions existing inside raw materials could easily raise stress concentration [3]. Surface indentations and machining defects increasing surface roughness could serve as crack originators [4]. Moreover, improper heat treatments also play an important role in the premature spring failure [5]. To ensure durability, improve component design, and reduce development costs, failure analysis of broken coil springs is a valuable tool for manufacturers and car parts suppliers.

There are large amounts of investigations on the topic of springs used on auto vehicles. Liu et al. [6] investigated shock absorption coil springs on motor cycle fractured earlier than the design expectation owing to the embrittlement of surface coating aggravated by insufficient shot peening which caused cracks initiated from the coating surface. The work of Prawoto et al. [7] could be considered as a summary of regular failure causes of automotive suspension springs in which digital simulations of stress distribution under various failure situations were also performed. Moreover, Zaccone [8] analyzed helical suspension springs used in compressors that failed due to the poor spring design. Zaccone also developed a theoretical mode to predict the fatigue life of compressor springs to reduce the evaluation time for spring failures and provide technical basis for the new spring design.

The auto vehicle industry has been continuously calling for the trend of weight reduction which consequently caused larger stresses in springs. Looking forward to satisfying the requirement of increasing stress level, it is important to improve the strength of spring materials. The work of Fragoudakis et al. [9] significantly improved the fatigue strength of 56SiCr7 spring steel by quenching, tempering, and shot peening, and underlined the effect of shot peening on the improvement in material fatigue life. Luo et al. [10] applied cyclic quenching of rapid heating and cooling on 51CrV4 spring steels to improve their mechanical strength by grain refinement, secondary phases, and micro/nano-twins whose incremental contribution percentages were also calculated, respectively. Moreover, Prabhakaran et al. [11] applied multiple laser peening surface modification process on dual-phase spring steel to improve its fatigue life and to repair pre-fatigued specimens. Also, Hattori et al. [12] investigated the effect of hot and cold working on the fatigue life of SAE 9254 spring steel.

The main aim of this work is to examine the failure reasons of one B48 coil spring on auto vehicles. This kind of spring could suffer from 100 thousand fatigue cycles under routine service; however, one spring failed after 2-month service (less than 20 thousand cycles). Local car parts manufacturers confirmed that the material chemical composition accorded with standard requirement, and only one spring failed from a batch of 500. Other objectives of this work includes following processes in different perspectives: (1) offering suggestions for manufacturers to prolong spring service time for saving costs; (2) serving as a reference in further investigation under similar circumstances.

Experimental

The B48 coil spring investigated in this research was made of ASTM 9260 spring steel whose main alloying elements were silicon and manganese. The manufacturing routine included three parts which were the raw material coiling into the spring shape, heat treatments, and surface treatments. Heat treatments were conducted at 880 °C for 15 min before being oil-quenched to ambient temperature and then tempered at 490 °C for 1 h to balance the strength and ductility. Surface treatments including acid pickling, phosphating, and electrophoretic paint were also performed to enhance its corrosion resistance.

Small chips from the failed coil spring were taken out near the fracture area by wire electro-discharging machine. These specimens were mounted, grinded, polished, and etched by using 4 vol.% Nital solution for 15 s. Both optical microscopy (OM, Olympus GX51) and scanning electron microscopy (FE-SEM, JSM-7001F, JEOL, Japan) techniques were used for micromorphology observation and fractography. Visual observation was also applied to reveal characteristics of the fractured region. To determine the chemical composition, EDS analysis affiliated on the SEM was also performed on fractured specimens. The microhardness was obtained by using HVS-1000 B microhardness tester at a load of 0.98 N underwelling for 15 s.

Results

Visual Observations

Observation of the Failed Spring

As shown in Fig. 1a and b, heavy wear marks could be identified on both horizontal and vertical external surfaces of the B48 coil spring. These two parts of marks are located on counterpositions which indicates that the spring was not installed properly and bore an additional stress to make its surface tore seriously. This installation deviation existed during the whole service time and therefore caused a high-stress concentration state.

Observation of the Fracture Surface

As shown in Fig. 1c, the crack initiated from the outer side of the spring chip. The crack initiation region locates on one edge rather than the intermedium of the fracture surface. Generally, coil spring is failed by the mode of fatigue due to the alternating load. However, there is no obvious characteristic of fatigue fracture which implies it suffered a complex stress situation. A small semicircular region is observed on one end of the fracture surface that we regard as the fatigue crack initiation and propagation region. It is worth noting that the area of crack initiation region (the semicircle) is much smaller than that of the whole fracture plane. The area of the total fracture surface could be estimated as about 50 mm^2, but the crack initiation region only occupies 5 mm^2 of it, which indicates that this coil spring was under an extremely high level of stress while at service. A fractured morphology inclined at about 45° could

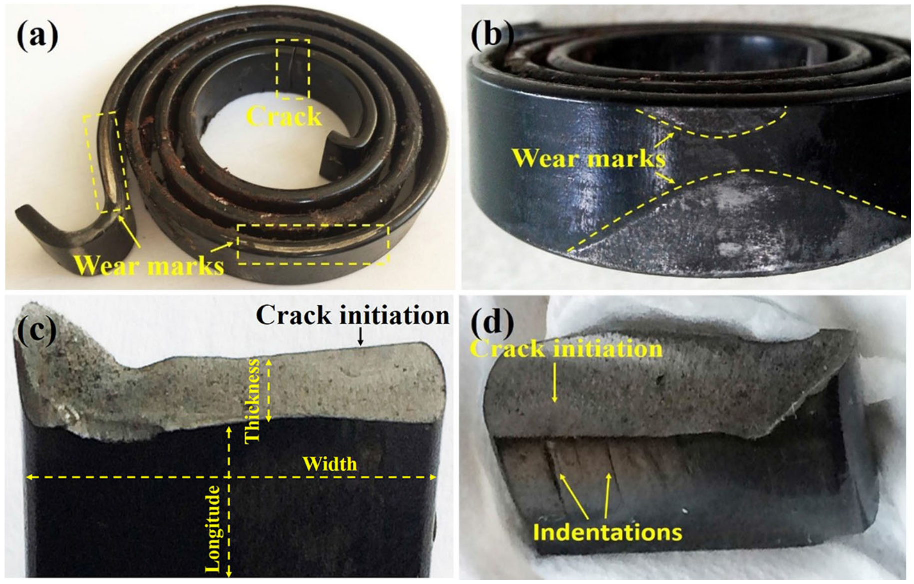


Fig. 1 (**a**) and (**b**) Photographs of the failed position and wear marks of the B48 coil spring; (**c**) and (**d**) Macro-morphology of the fractured surface

be clearly observed on the other end of the failure plane. This indicates that the crack propagated from the semi-circle along the width direction and shear cut the spring at the inclined region (final rupture region). This crack propagation mode is quite different from the similar coil spring failed under a fatigue rupture model. Figure 3b shows the macro-morphology of fracture surface of the similar type of coil spring that we have analyzed before. It could be observed that, under the service load, crack initiated from the center of one intersecting surface and propagated along the direction of thickness. Also, this fatigue fracture surface shows a large expansion region and clear fatigue arcs, which are typical fatigue fracture characteristics. As shown in Fig. 1d, several surface indentations are visible and one of them reaches exactly to the heart of the crack initiation region. These indentations could be produced during coiling process involuntarily. The exterior indentation is apparently one of the reasons that accelerate the formation of crack.

Microhardness Tests

Vickers hardness tests were performed on the cross-section samples which show a hardness of 420 ± 5 Hv. This is a quite qualified hardness value after treatments mentioned above. Tensile strength of this material could be determined empirically by the following equation [13]:

$$\sigma_{TS}(\text{in MPa}) = 3.2\,\text{Hv}(\text{Hv} = \text{the value of Vickers hardness}) \quad \text{(Eq 1)}$$

The tensile strength of this spring specimen is determined as 1340 MPa empirically since it is impossible to produce a standard tensile test specimen from the received spring. The instantaneous ruptured area is caused by the tensile load which could be estimated as stress multiply by the area of ruptured surface. Therefore, the service stress could be determined as 1000 MPa roughly.

Material Microstructure

OM specimens were taken from both transversal and longitude directions and mounted to exhibit their surface characteristics. Figure 2 shows the OM images of prepared specimens after etching. It reveals that the matrix microstructures of the two directions are all tempered troostite and a small amount of tempered sorbite. This is in accord with standard microstructure after quenching and tempering of this material. Indentations could also be observed in Fig. 2b and c which were produced under manufacturing process.

Microscopic Examination

Investigation of Crack Initiation Region

As shown in Fig. 3a, district "A" represents the crack initiation region (the semicircle), and Fig. 4 shows the SEM images of this region. One of the macro-indentations reaching to the center of the semicircle could also be observed in SEM micrographs (Fig. 4a). The higher-magnification micrograph (Fig. 4b) shows radiating ridges emanating from the indentation tip. This pattern is caused by crack initiation, thus indicating that the semicircle is the crack initiation and extension region. Figure 4c shows a globular microstructure which is abnormal in the crack initiation region. EDS analysis indicates the main chemical

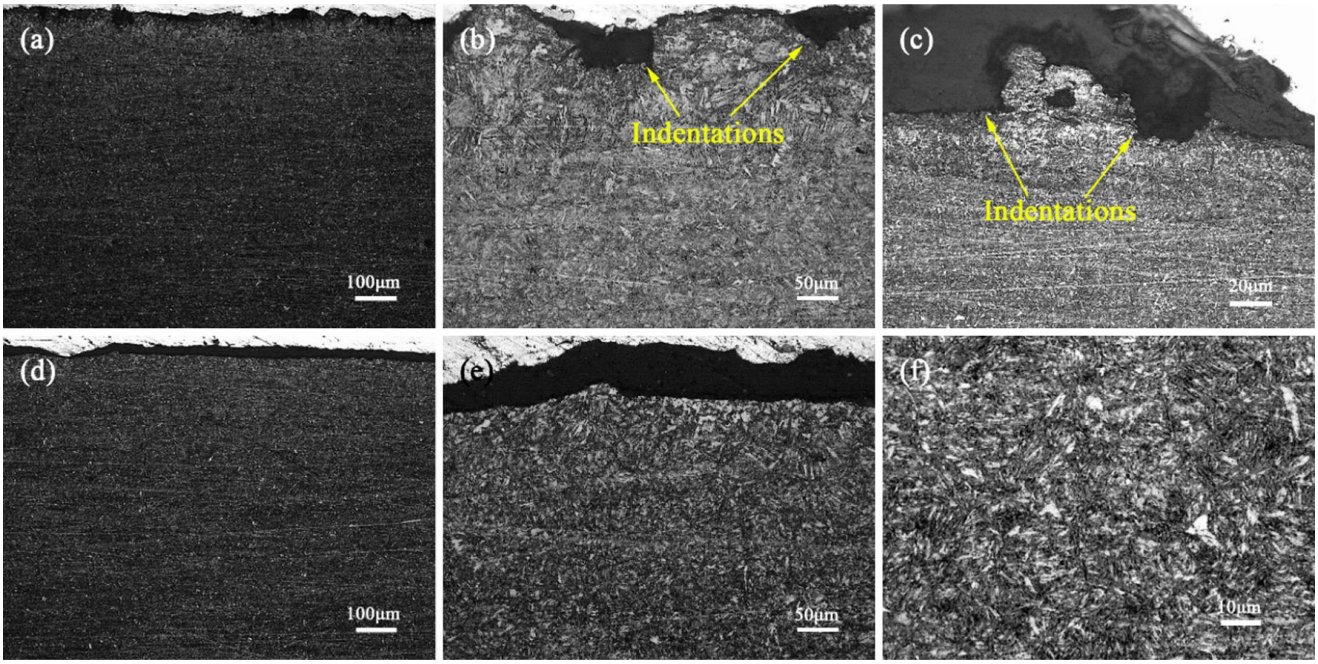


Fig. 2 OM images of the near surface of transversal (**a–c**) and longitude (**d**) and (**e**) specimens. (**f**) The matrix microstructure in higher magnification

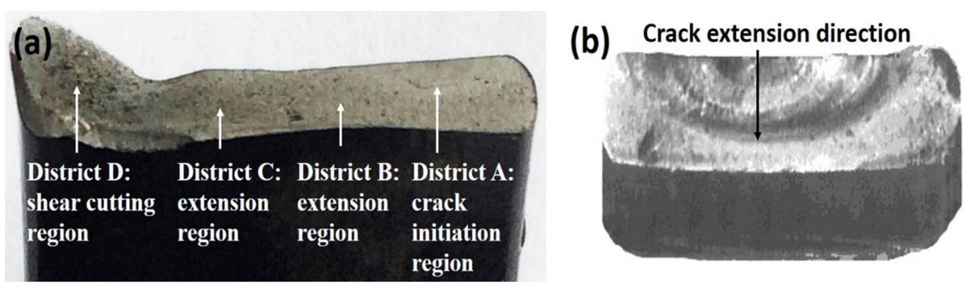


Fig. 3 (**a**) Illustration of districts on which SEM observations were conducted. (**b**) The common fracture surface morphology of B48 coil spring

composition is Fe, Zn, P, O, Si, C. The main chemical elements in paint are C, Si, Al, and the element of P may penetrate inside during the phosphating process. This abnormal phenomenon implies microcracks existed in the indentation region before installation.

Investigation of Crack Extension and Shear-Cutting Region

Figure 5 shows the SEM morphology of district "B". District "B" is defined as crack extension region on which secondary cracks that are vertical to the fracture surface could be observed (Fig. 5c and d). A brittle fracture morphology was revealed in this extension region which indicated cracks propagated under a high stress level. Due to the combined effect of indentation, improper installation, and service load, this region was under a triaxial stress status making this material more brittle.

District "C" is also defined as a crack extension region which exhibits a much different micromorphology from district "B". Fatigue striations and dimples could be observed in Fig. 6a and b which are chief characters of fatigue fracture [14]. This indicates that part of the coil was failed by the fatigue fracture mechanism. The final shearing district "D" (Fig. 7) also shows fatigue striations and a ductile rupture mode.

Discussions

According to common failure cases of B48 coil (Fig. 3b), under a normal alternating load, fatigue fracture mode is the major failure mechanism, and the crack initiated from the center of the rupture surface and then propagated along the direction of thickness. However, in this case, crack

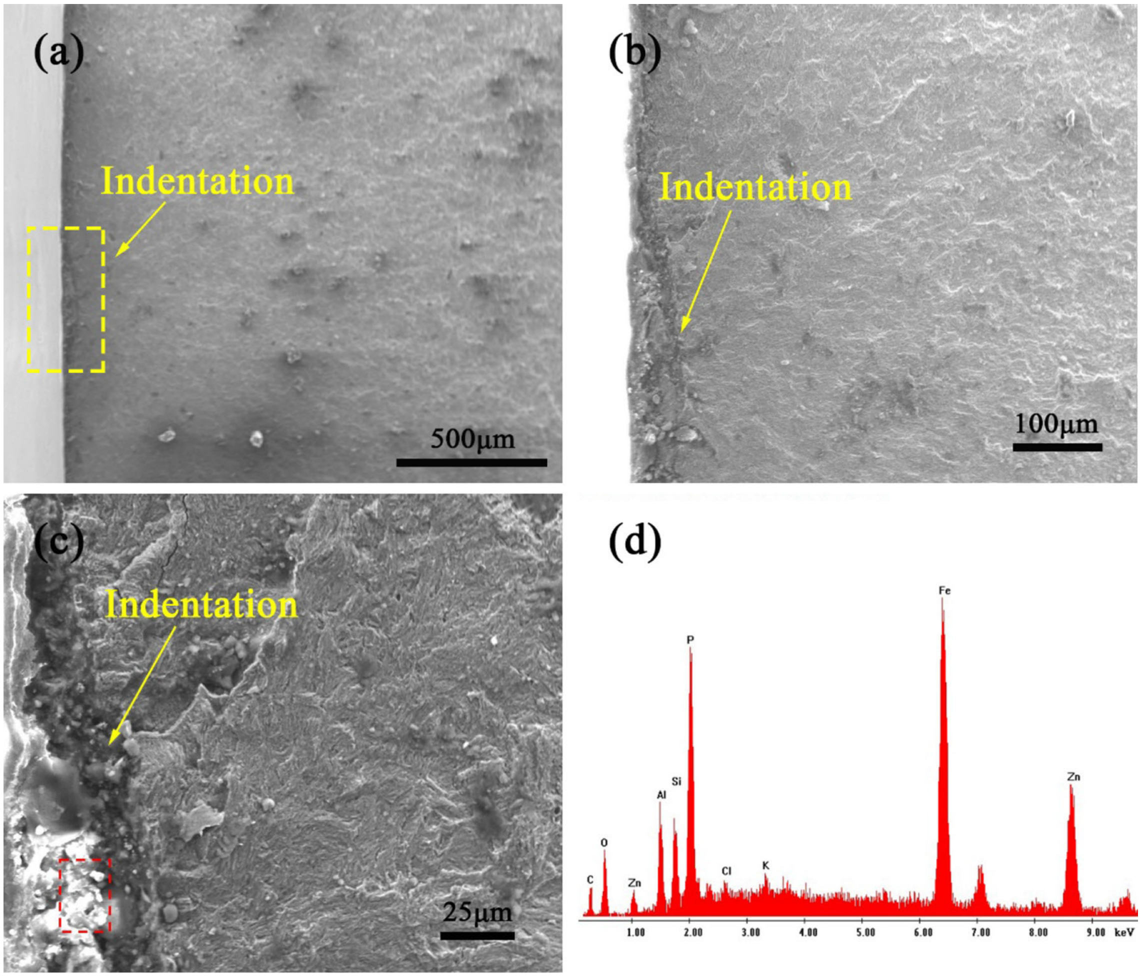


Fig. 4 (**a**)–(**c**) SEM micrographs of district "A" of the fracture surface. (**d**) EDS results on the region marked in (**c**)

initiated from one edge of the coil spring chip and propagated along the direction of width (Fig. 1c). As shown in Fig. 3a, the failure plane could be divided into different districts, and they are not on the same altitude which denotes additional stresses were loaded on the B48 spring while at service. Under a regular service load, the final fracture region "D" usually locates on the side with smaller radius of coil chip and is vertical to the longitude axis. Meanwhile, the final rupture region in this B48 coil spring is situated on one side of width direction which also indicates the existence of additional stress. The common failure cases we have analyzed before (Fig. 3b) show a large fatigue extension area and a much smaller final rupture region. The failure morphology of this case (as shown in Fig. 3a) exhibits a large area of final rupture region. This indicates the B48 coil spring analyzed in this work suffered a high service stress which could be estimated to 1000 MPa. The micromorphology of crack extension region near the initiation region (Fig. 5c and d) shows secondary cracks which indicates the existence of three-dimensional state of stress. These secondary cracks could further manifest the crack propagated under a heavy load. All these experiments results and analyses could be summarized as that this B48 coil spring was under an extremely high-level stress while at service causing the premature failure.

As shown in Fig. 1a, wear marks resulting from the improper installation could be observed on the top surface of this B48 coil spring. This is one of the primary sources of additional stresses. Two indentations could be observed at one lateral surface of the failed spring chip as marked in Fig. 1d. However, one of the indentations extended exactly to the center of the crack initiation region as mentioned above. Microcracks formed in the tip of the indentation and caused a stress concentration state. This indentation served as crack initiation point from which crack propagated ultimately reaching opposite edge of fracture surface and causing final failure [15]. Severe wear marks as shown in Fig. 1b could be observed on the lateral surface. This part of marks resulted from the improper installation which is

Fig. 5 SEM micrographs of district "B" of the fracture surface

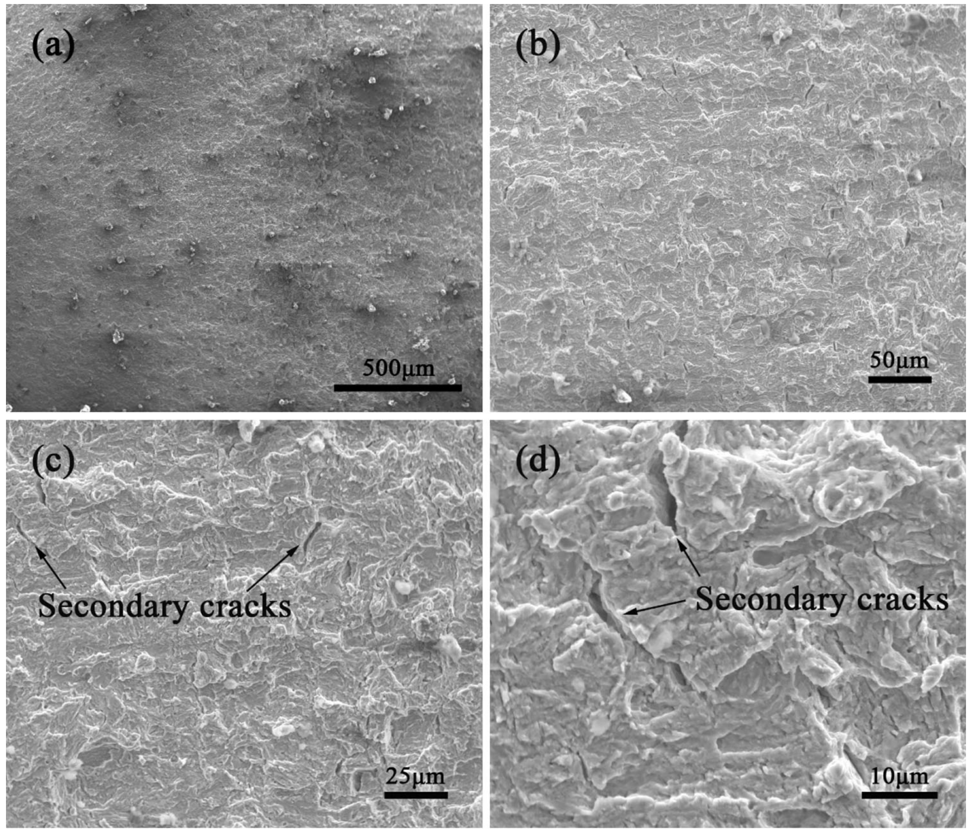
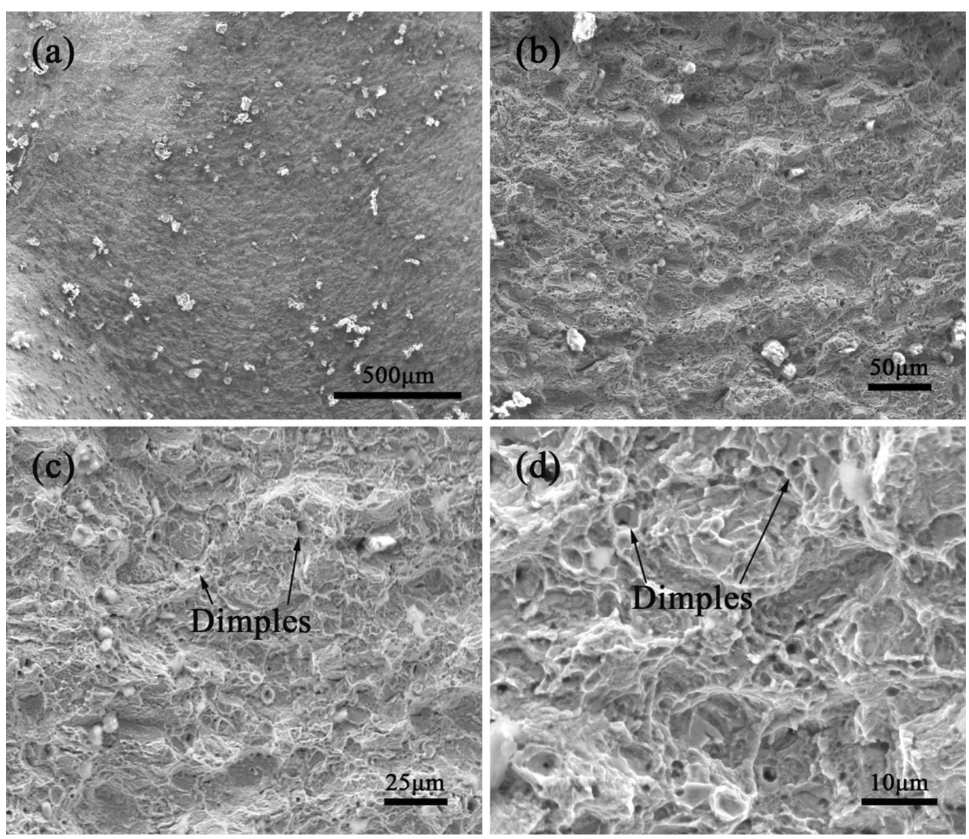


Fig. 6 SEM micrographs of district "C" of the fracture surface



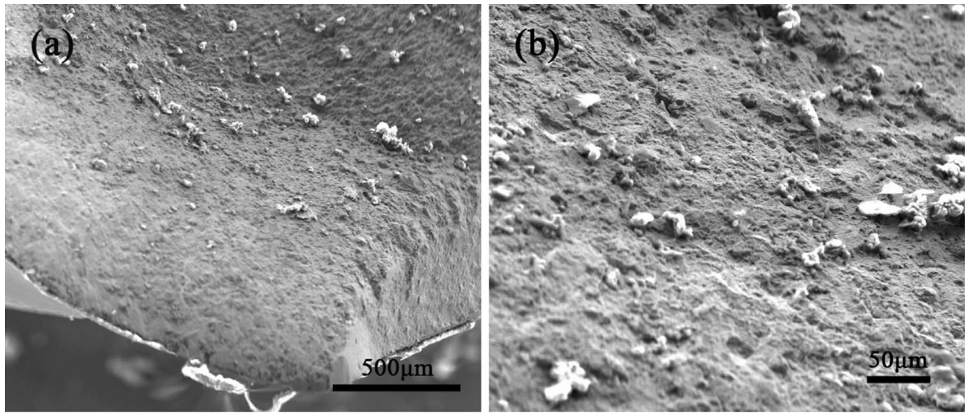


Fig. 7 SEM micrographs of district "D" of the fracture surface

another source of additional stress. Inclusions could be observed in SEM images near the crack initiation region which also affected the fatigue cycle numbers of a material.

According to the analyses and discussions above, the fracturing processes of this B48 coil spring could be summarized as: Due to the existence of installation deviation, indentation, and inclusions near the crack initiation region, stress concentration was raised and a fatigue crack initiation was formed in one of the indentations under a short period of service. This crack initiation located on one side of the failed spring chip rather than the center of the fractured surface. Under a high stress level, crack propagated promptly along the width direction of the spring chip. With the crack extension and decrease in connected surface, the coil spring failed because of the excessive tensile stress, and a large area of instantaneous fractured region together with a shear lip was formed on the fractured surface.

Conclusions

In this study, fractured spring surface was examined by using SEM, EDS analysis, and visual observation. Microstructure and hardness of the matrix material were revealed by optical microscope and Vickers hardness tester, respectively. The fracture mechanisms of this coil spring were analyzed, and the causes of early fracture were investigated. Main conclusions can be drawn as follows:

1. The microstructures of the matrix material of this fractured coil spring are tempered troostite and tempered sorbite which remain in the standard microstructure.
2. The failure of this coil spring was initiated by the microcracks induced from surface indentations and finally fractured by the crack fracture mode of fatigue failure.
3. This coil spring was under an alternating service stress together with additional stress which resulted in a high-stress state. Under such high-level stress, crack initiated from the tip of one indentation and propagated promptly across the fractured surface. The high-level stress this spring suffered was resulted from the installation deviation.

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