

# Analysis and Research on Common Failure Modes of Internal Combustion Engine Springs

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**How to cite this paper:** Dai, L.Q., Liu, L., Liu, N., Lang, K.X. and Sun, W.J. (2025) Analysis and Research on Common Failure Modes of Internal Combustion Engine Springs. *Journal of Materials Science and Chemical Engineering*, **13**, 77-95.

<https://doi.org/10.4236/msce.2025.139006>

**Received:** August 13, 2025

**Accepted:** September 16, 2025

**Published:** September 19, 2025

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## Abstract

In order to improve the service reliability of internal combustion engine springs, the spring steel sample in this paper is an experimental test piece, the material is chromium-silicon (55CrSi, 60CrSiA), chromium-vanadium (50CrVA), etc., using macroscopic observation, scanning electron microscopy fracture analysis, energy spectrum EDS component detection and metallographic inspection and other methods to detect common failure modes such as quenching cracks, folding, pits, corrosion pits, mechanical damage, scratches, inclusions, The results show that the quenching cracks are due to the superposition of thermal stress and microstructure stress during the quenching process. Folding and inclusions are the main sources of stress concentration with defects in the manufacturing process; corrosion is mostly related to the high-temperature service environment. As the origin point of fatigue cracks, the pits on the surface of the spring destroy the continuity of the material and significantly reduce the fatigue strength, causing early fatigue fracture. This paper clarifies the key failure forms and root causes of internal combustion engine springs, and proposes a set of scientific and systematic electron microscopy analysis methods, which cover the analysis and characterization of the micro-composition of the fracture anomaly area, the surface distribution and line distribution of elements, inclusions and other chemical elements of defects, evaluate the influence of parts physical and chemical indicators on the causes of fracture, and provide theoretical support and improvement direction for the reliability optimization of internal combustion engine springs.

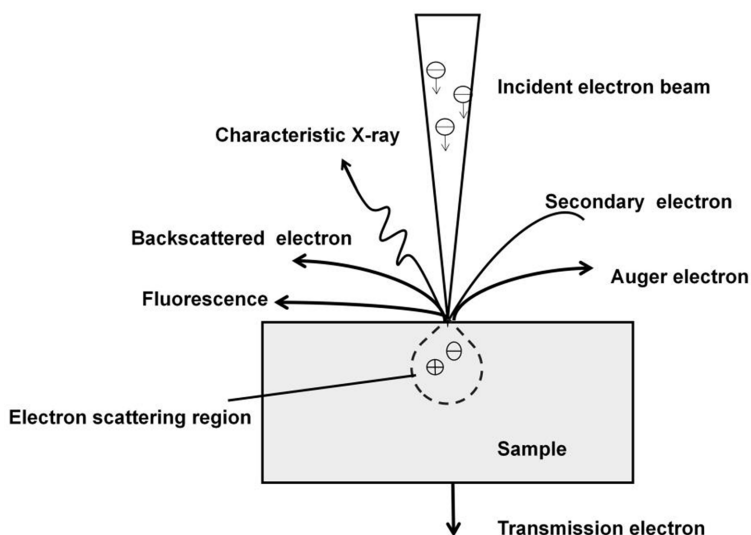
## Keywords

Internal Combustion Engine, Spring, Scanning Electron Microscopy, Failure Mechanism

## 1. Introduction

Springs are one of the key functional components of internal combustion engines, which can use the high elasticity and special structure of their own materials to convert mechanical energy into deformation energy, or convert deformation energy into mechanical energy [1]. Common ones, such as valve system springs, piston system springs, turbocharging system springs, etc., can provide precise elastic force and rapid response during driving, and their working status has a decisive impact on ensuring driving safety. The common function of the valve spring is to ensure the reliable closure of the valve and the valve seat by continuously applying axial load, balance the inertial load of the gas distribution system, and prevent the phenomenon of motion instability. For example, the piston system spring uses a corrugated spring or coil spring, which eliminates the mating gap between the piston pin and the connecting rod by providing continuous radial preload to ensure the stable operation of the piston assembly. Functional failure of the spring system is one of the most destructive failure modes of internal combustion engines [2] [3], and if the critical failure of the spring system of the internal combustion engine is critical, the instantaneous release of elastic energy storage is likely to cause major safety accidents. Therefore, quickly and accurately determining the failure method and cause is crucial to finding quality problems and eliminating hidden dangers.

## 2. Analyze the Function Description and Principle of the Equipment



**Figure 1.** Schematic diagram of the signal when the electron beam acts.

Scanning electron microscopes generally include vacuum systems, electron beam systems, and imaging systems. The working principle of scanning electron microscopy is to interact with the sample by focusing the electron beam and exciting the signal on the sample surface to generate signals, which will be detected by the

detector, and display the scanning image synchronized with the electron beam. The signals that detect the interaction of electron beams with samples are such as elastic scattering leading to high-energy reflected electrons, electrons colliding with nuclei to produce backscattered electrons (BSE), and inelastic scattering of secondary electrons (SE), characteristic X-rays, Auger electrons, cathodic fluorescence, etc. [4]-[6], and the schematic diagrams of various signals during electron beam action are shown in **Figure 1**.

### **3. Experimental Research**

#### **3.1. Physical and Chemical Properties**

According to the fracture mode of parts, it is divided into edge crystals, cleavage, quasi-cleavage, fatigue, toughness, slippage, corrosion, etc., and the stress concentration of fracture sources such as bumps, knife marks, cracks, non-metallic inclusions, etc.

#### **3.2. Inspection Method**

##### **3.2.1. Number of Test Pieces**

At least 3 - 5 samples of each failure mode were analyzed to ensure representative results.

##### **3.2.2. Sample Preparation Method**

Use mechanical processing or wire EDM to cut the sample suitable for scanning electron microscope analysis and observation, smooth the bottom of the sample, use a brush to clean the surface to remove surface debris, immerse it in anhydrous ethanol for 10 - 15 minutes ultrasonic cleaning, clean the surface of contaminants, such as oil stains, after taking it out, there should be no foreign matter on the surface of the sample, clean and dry before setting aside.

##### **3.2.3. Observation and Analysis of the Morphology of the Fracture**

The fracture should be placed separately before observation to prevent contamination of the sample.

During macroscopic observation, the fault location, crack propagation direction, and the size of the final fault area should be recorded to preliminarily judge the failure mode.

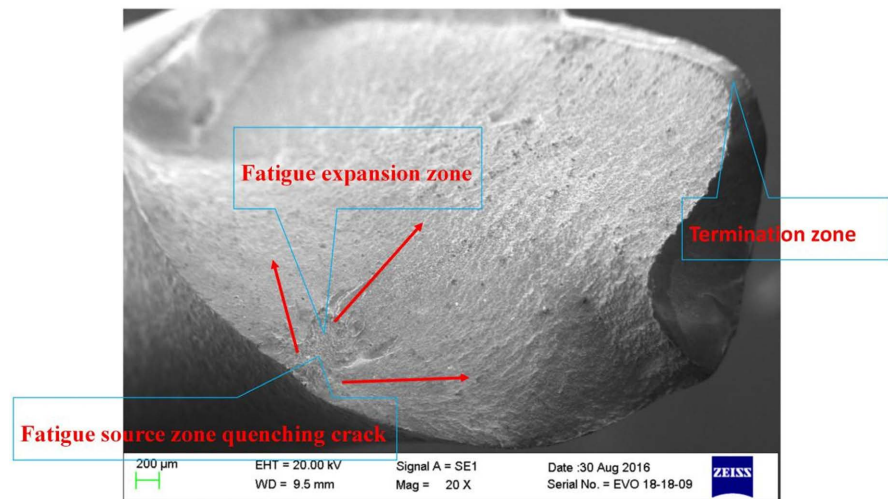
During microscopic analysis, the spring sample should be placed in the sample chamber, fixed on the sample stage with conductive glue, the surface morphology should be positioned at low magnification of the fracture, and the source area, expansion area, final fault area, and valuable area should be observed at gradual magnification, and clear SEM image photos should be taken.

### **4. Analysis of Results**

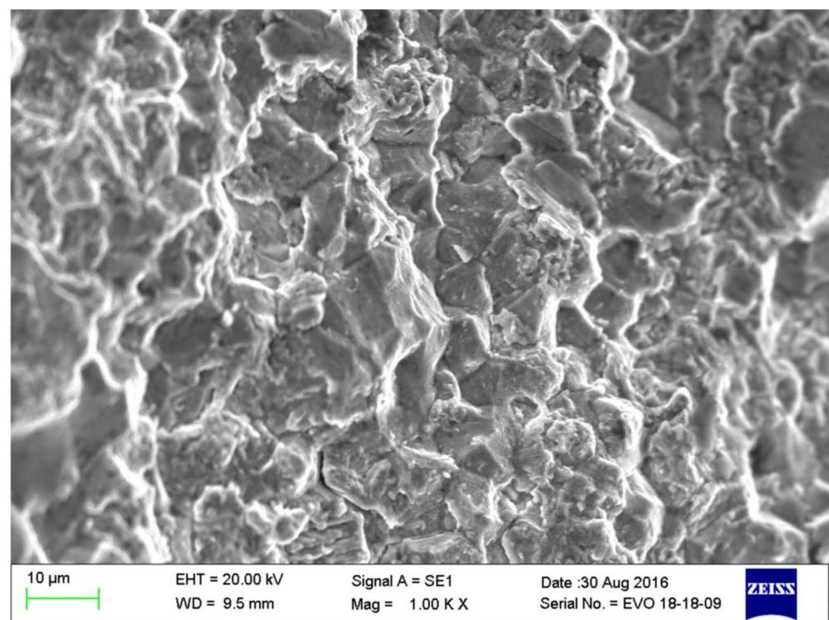
#### **4.1. Fatigue Fracture Caused by Quenching Cracks**

Under normal circumstances, the spring is subjected to the torsional warping force of bending, and its fracture has obvious radial fatigue propagation traces

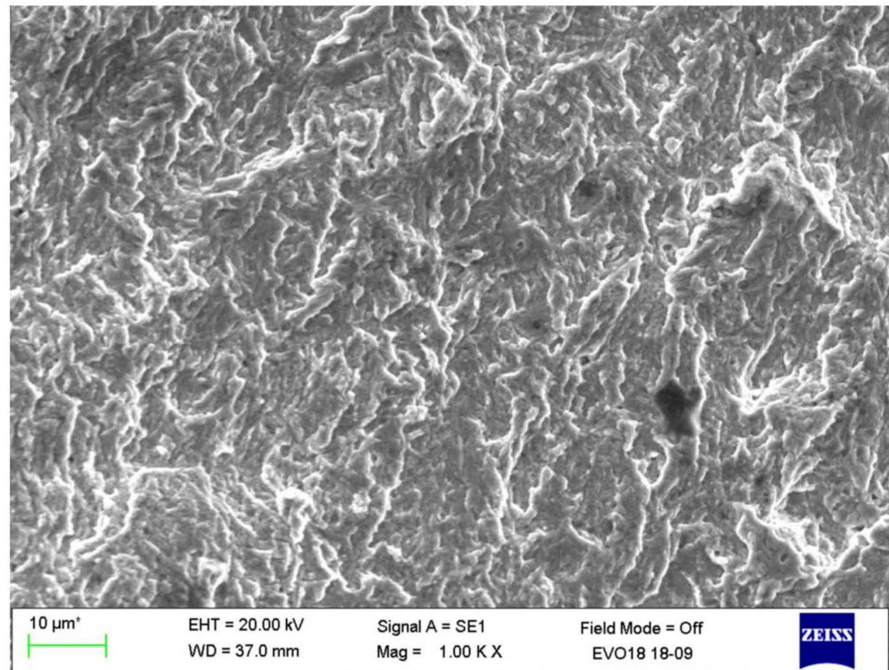
from the source area to the surrounding area under the low fold and microscopic morphology, the fatigue source area is mainly fractured along the crystal, the fatigue expansion area is obvious, and the final fault area is mostly U-shaped, generally ductile fracture, serious oxidation, and the lead attachment is often accompanied by lead adhesion in the spring quenching crack area of the lead bath heating. The morphology of the fracture caused by spring quenching cracks is shown in **Figure 2**. The micromorphology of the fatigue fracture along the fracture and the fatigue propagation zone in the fracture fatigue source area are shown in **Figure 3** and **Figure 4**, and the lead adhesion in the electron microscopy spectroscopy analysis of the spring quenching crack area is shown in **Figure 5**.



**Figure 2.** Fracture morphology caused by spring quenching cracks.



**Figure 3.** Microscopic morphology of fatigue source area caused by spring quenching cracks.



**Figure 4.** Microscopic morphology of fatigue fracture propagation zone caused by spring quenching cracks.

Spectral Processing:

Peaks that may be ignored: 0.266 keV

Processing Options: All Analyzed Elements (Normalized)

Number of repetitions = 2

Standard Sample:

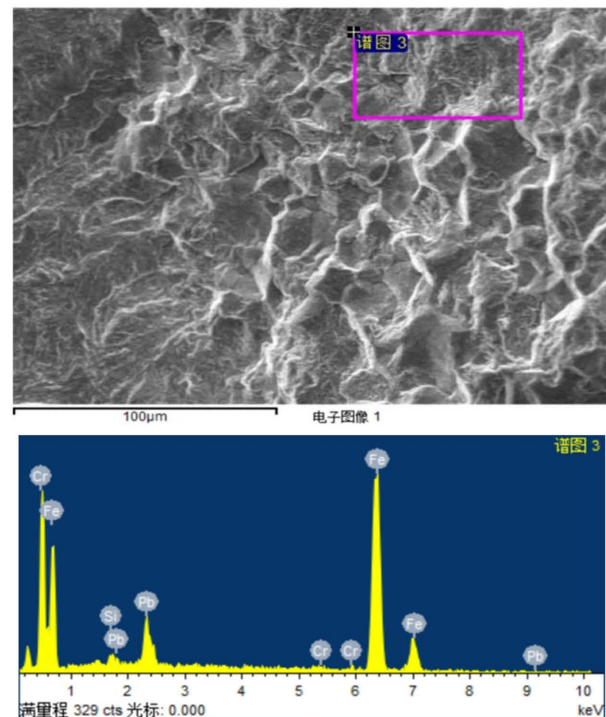
Si SiO<sub>2</sub> 1-Jun-1999 12:00 AM

Cr Cr 1-Jun-1999 12:00 AM

Fe Fe 1-Jun-1999 12:00 AM

Pb PbF<sub>2</sub> 1-Jun-1999 12:00 AM

Element	Weight	Atom
	Percentage	Percentage
Si K	1.29	2.91
Cr K	0.48	0.58
Fe K	80.10	90.95
Pb M	18.14	5.55
Total	100.00	

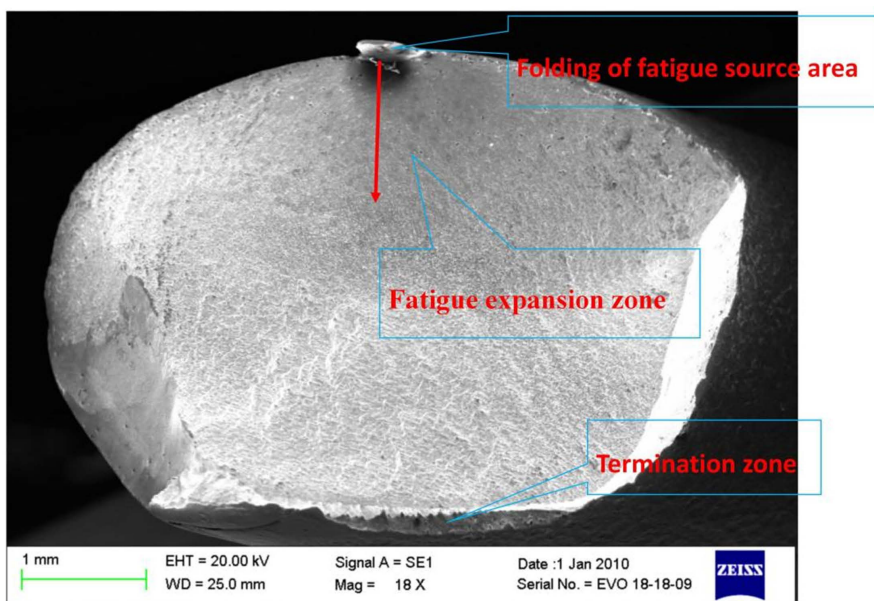


**Figure 5.** Electron microscopy analysis results of the spring quenching crack zone.

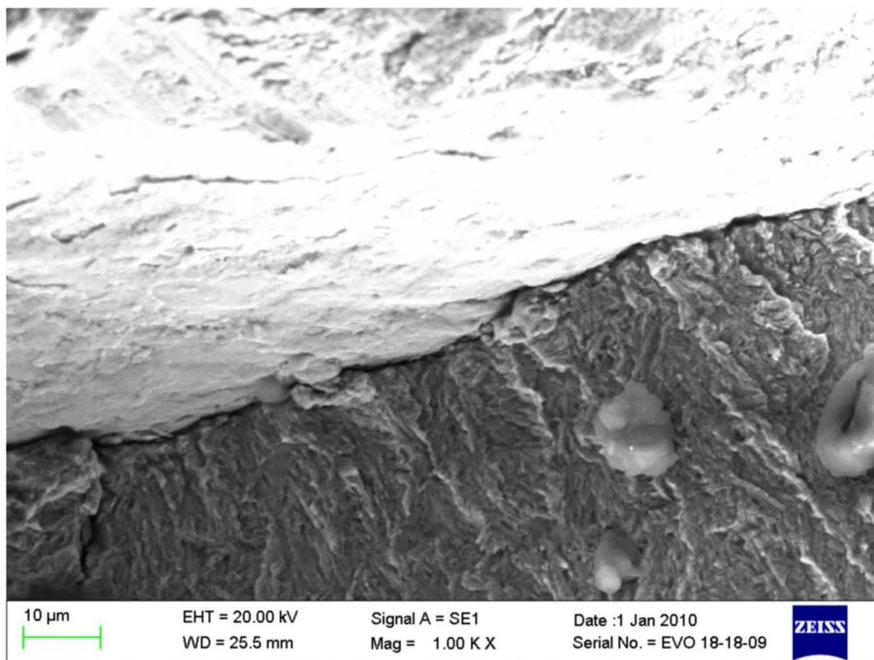
## 4.2. Fatigue Fracture Caused by Folding

Folding refers to the interlayer rolling of materials during the manufacturing pro-

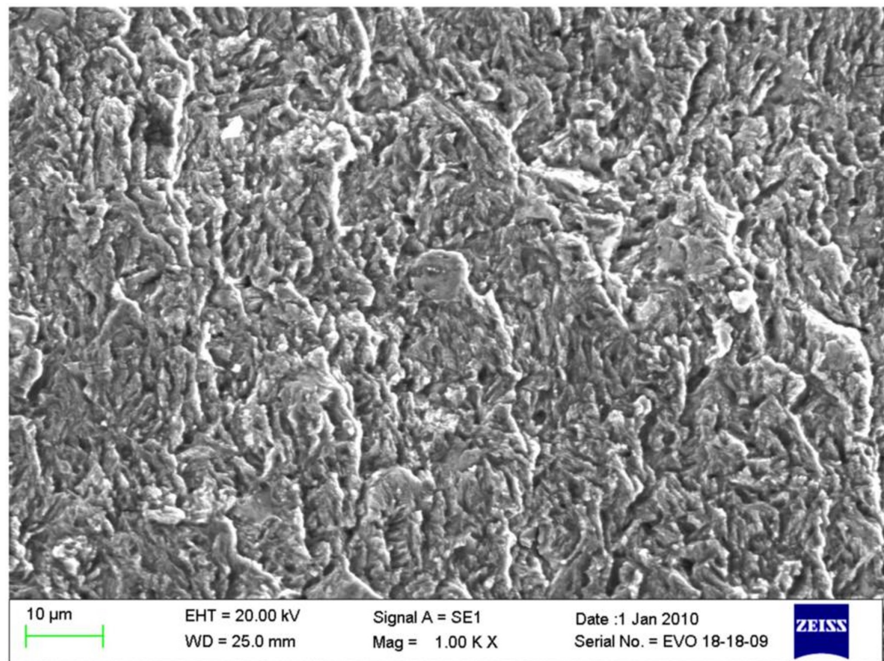
cess to form a kind of “false skin”, which is improperly cold-processed and usually presents continuous or intermittent straight lines, furrows, or fish scale cracks. The fracture in the fatigue source area is severely oxidized, and the two sides are concave and protruding, and the fatigue extension area is obvious. The morphology of the fatigue fracture caused by spring folding is shown in **Figure 6**, and the microscopic morphology of the fatigue source area, fatigue propagation zone, and final fault area caused by spring folding are shown in **Figures 7-9**.



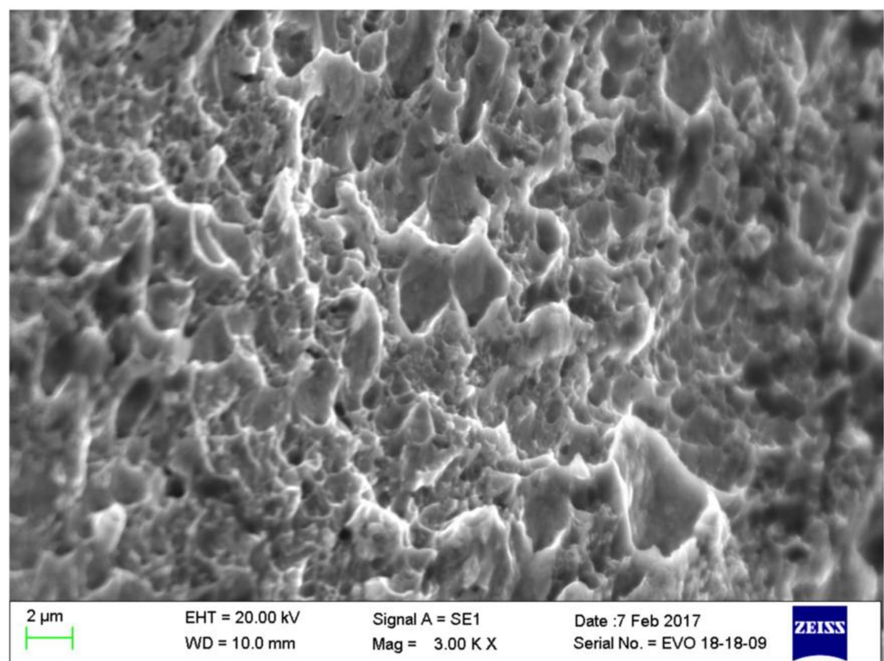
**Figure 6.** Morphology of fatigue fracture caused by spring folding.



**Figure 7.** Microscopic morphology of the fatigue source area caused by spring folding.



**Figure 8.** Microscopic morphology of fatigue propagation zone caused by spring folding.

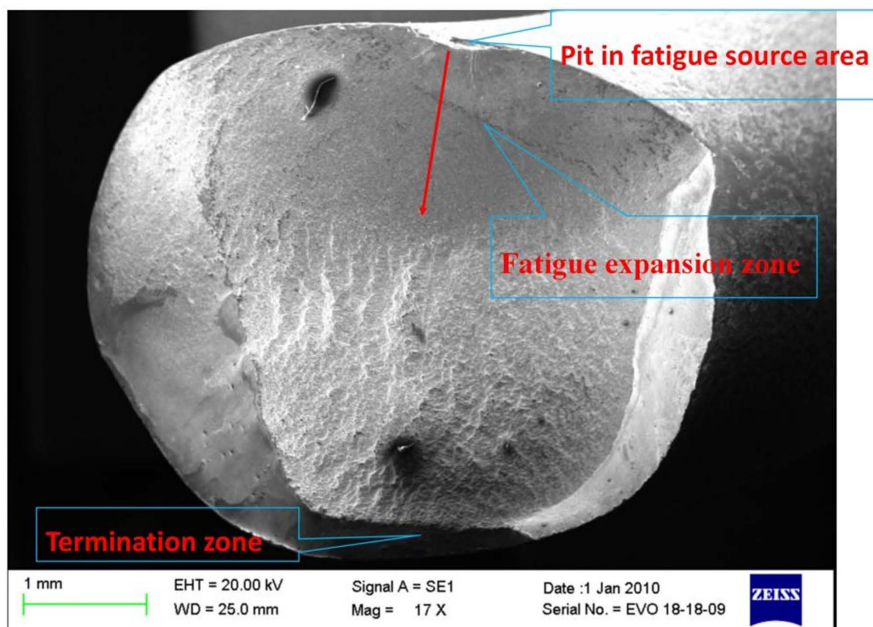


**Figure 9.** Microscopic morphology of the fatigue fracture final fault zone caused by spring folding.

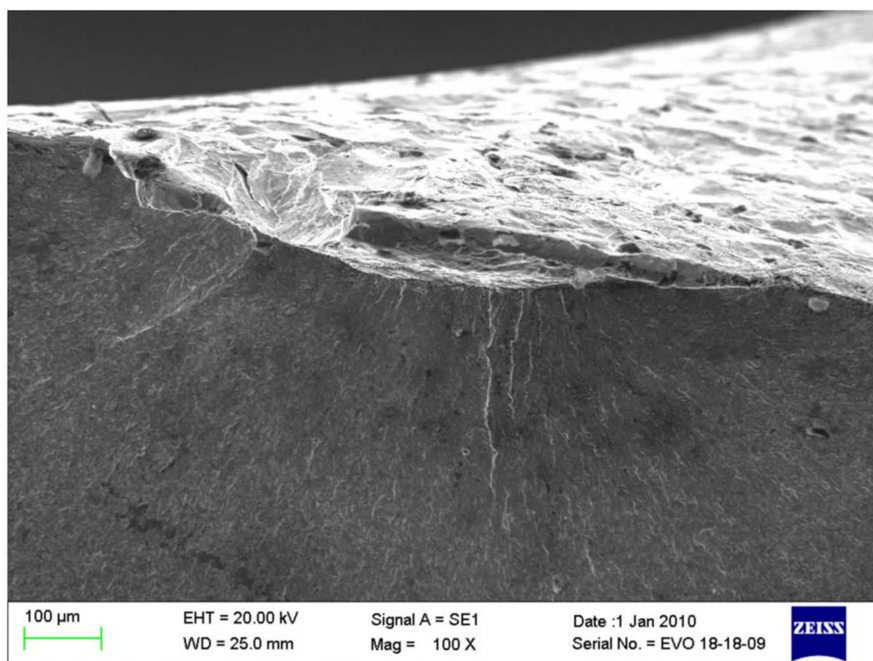
### 4.3. Pits Cause Fatigue Fracture

Pits are mechanical impacts that form small depressions locally. The fracture of the fatigue source area has obvious depressions and severe oxidation, independent or small amounts, mostly caused by mechanical damage, obvious fatigue flaring

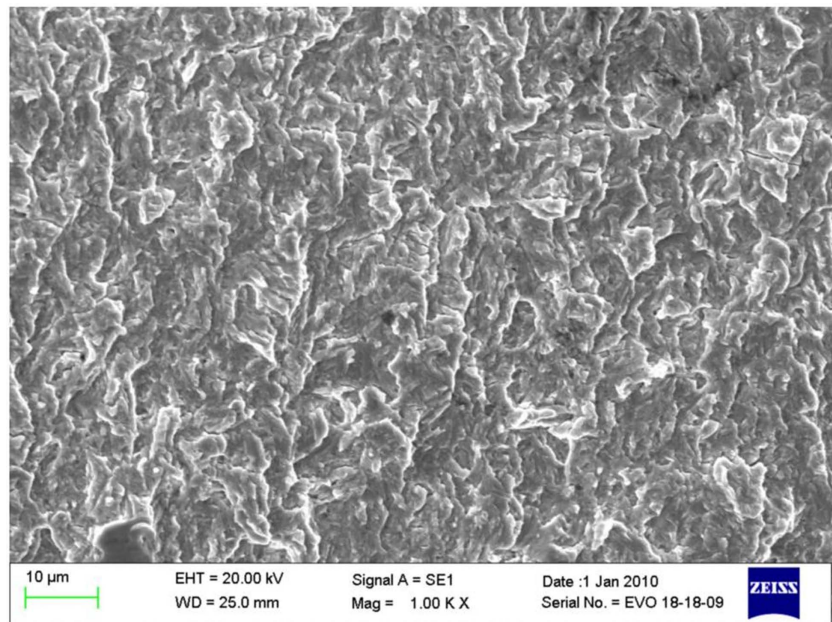
in the fatigue expansion area, and most of the final fault area is U-shaped, generally ductile fracture. The morphology of the fracture caused by the spring pit is shown in **Figure 10**, and the micromorphology of the fatigue glow in the fatigue source area and fatigue expansion area caused by the spring pit is shown in **Figure 11** and **Figure 12**.



**Figure 10.** Morphology of fatigue fracture caused by spring pits.



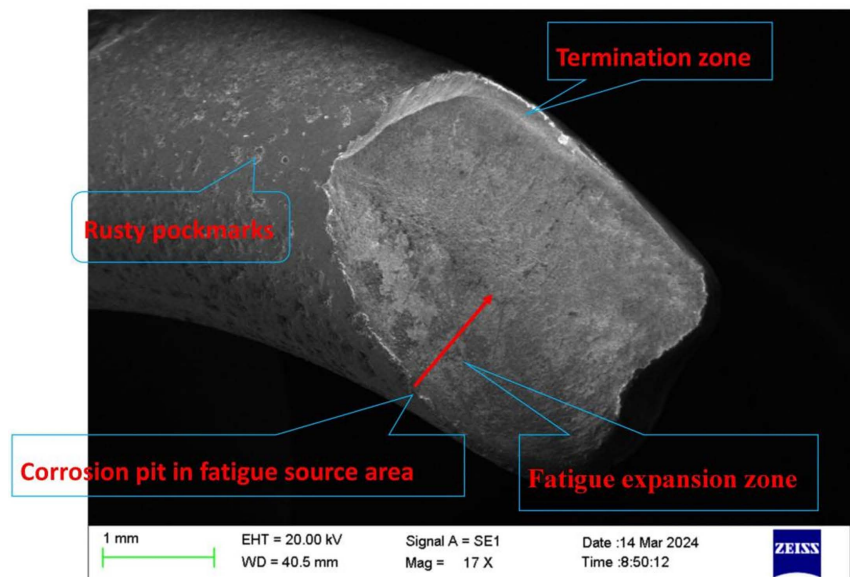
**Figure 11.** Microscopic morphology of the fatigue source area caused by fatigue fracture due to spring pits.



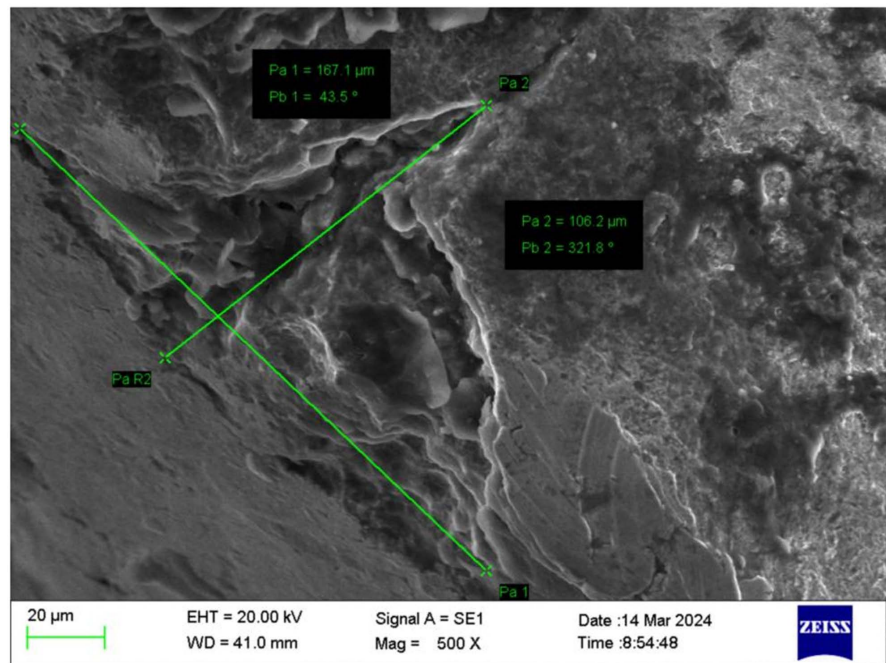
**Figure 12.** Microscopic morphology of the fatigue propagation zone caused by fatigue fracture due to spring pits.

#### 4.4. Corrosion Pit Causes Fatigue Fracture

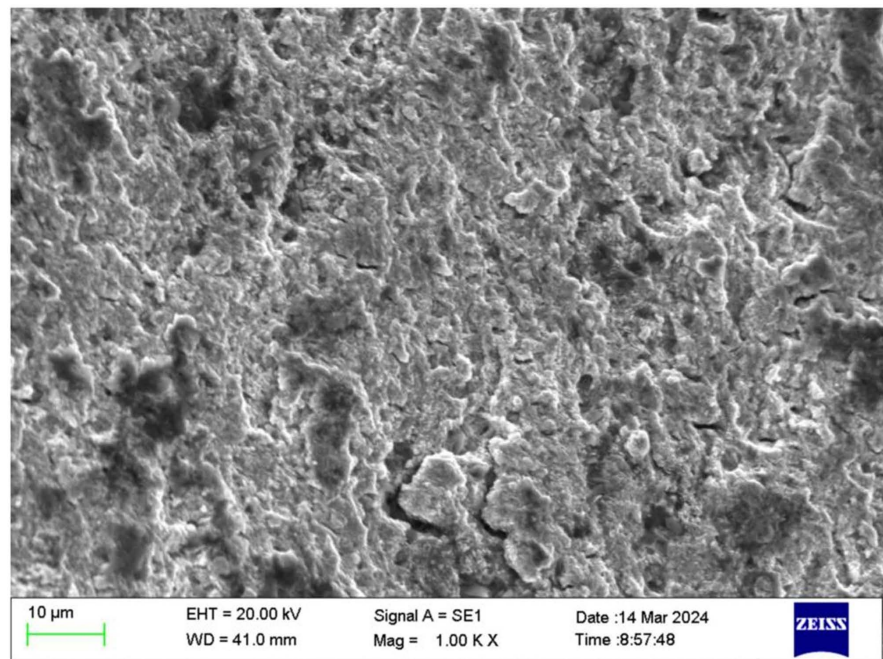
There are obvious corrosion pits and serious oxidation at the fracture in the fatigue source area, and the surrounding or the entire spring surface is densely corroded with pits, which are mostly caused by rust on the surface of the spring wire. The morphology of the fatigue fracture caused by the spring corrosion pit is shown in **Figure 13**, and the microscopic morphology of the fatigue source area and fatigue propagation area caused by the spring corrosion pit are shown in **Figure 14** and **Figure 15**.



**Figure 13.** Morphology of fatigue fracture caused by spring corrosion pits.



**Figure 14.** Microscopic morphology of the fatigue source area caused by spring corrosion pit fatigue fracture.

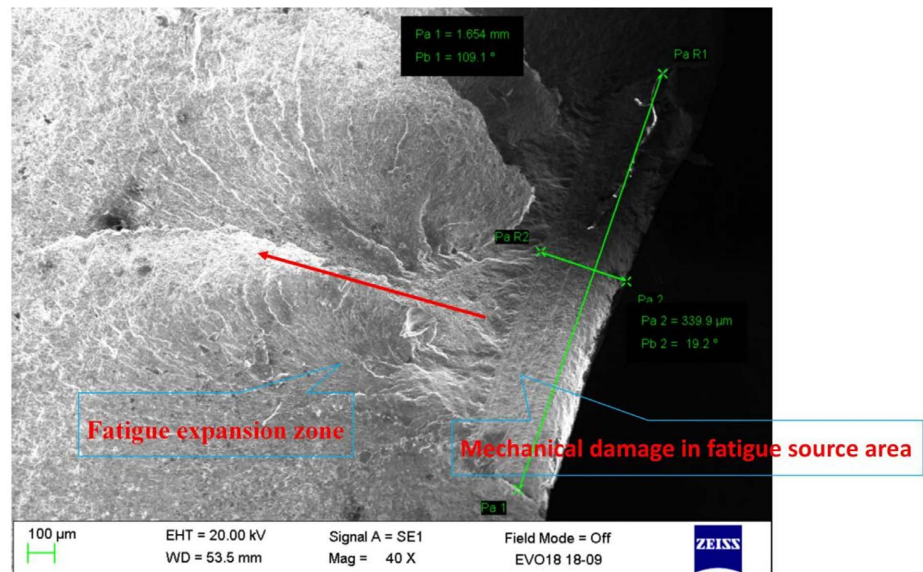


**Figure 15.** Microscopic morphology of the fatigue propagation zone caused by spring corrosion pits.

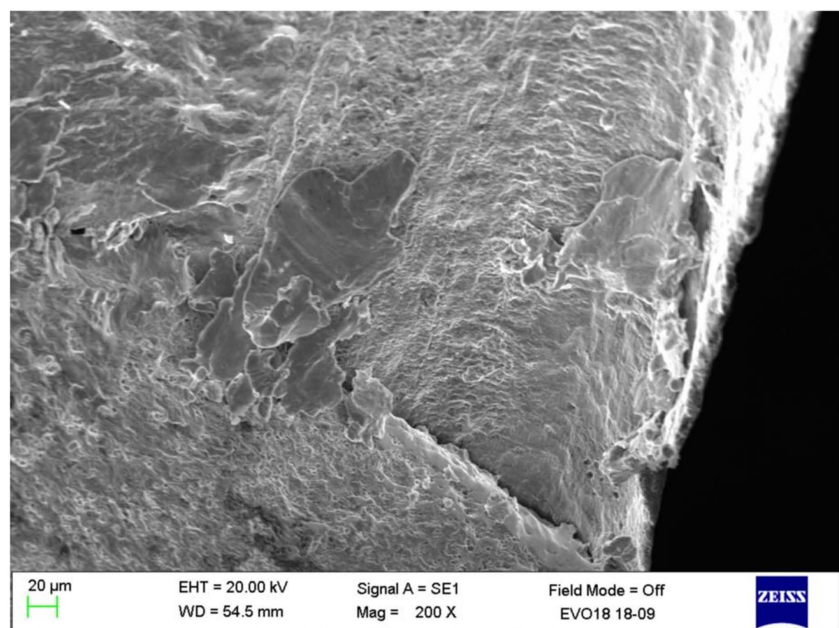
#### 4.5. Fatigue Fracture Caused by Mechanical Damage

The fracture of the fatigue source area has obvious traces of mechanical damage from the source area to the surrounding area under the low magnification and microscopic morphology, the fracture of the fatigue source area has obvious traces

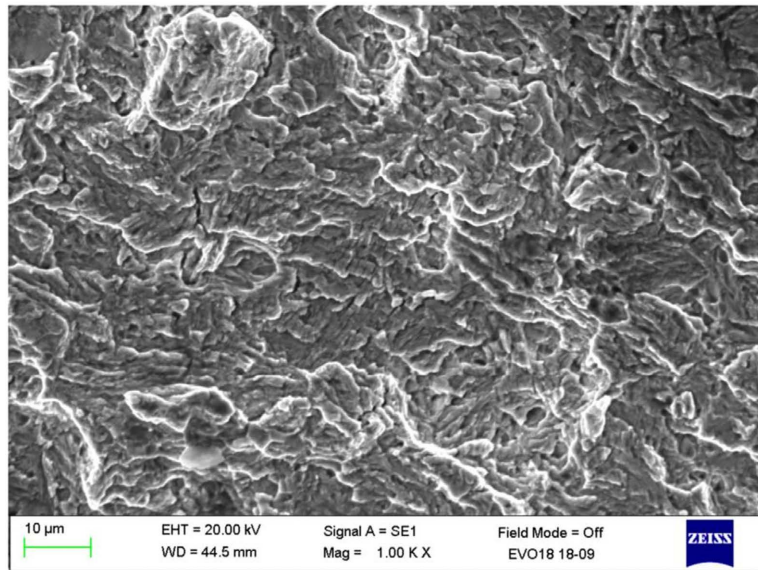
of mechanical damage, severe oxidation, the fatigue glow pattern in the fatigue expansion area is obvious, the final fault area is mostly U-shaped, generally the ductile fracture, the morphology of the fatigue fracture caused by spring mechanical damage is shown in **Figure 16**, the microscopic morphology of the fatigue source area and fatigue expansion area caused by spring mechanical damage is shown in **Figure 17** and **Figure 18**, comprehensive force analysis, The characteristics such as fracture morphology can determine that the spring is a bending and torsional composite fatigue fracture under mechanical load.



**Figure 16.** Morphology of fatigue fracture caused by spring mechanical damage.



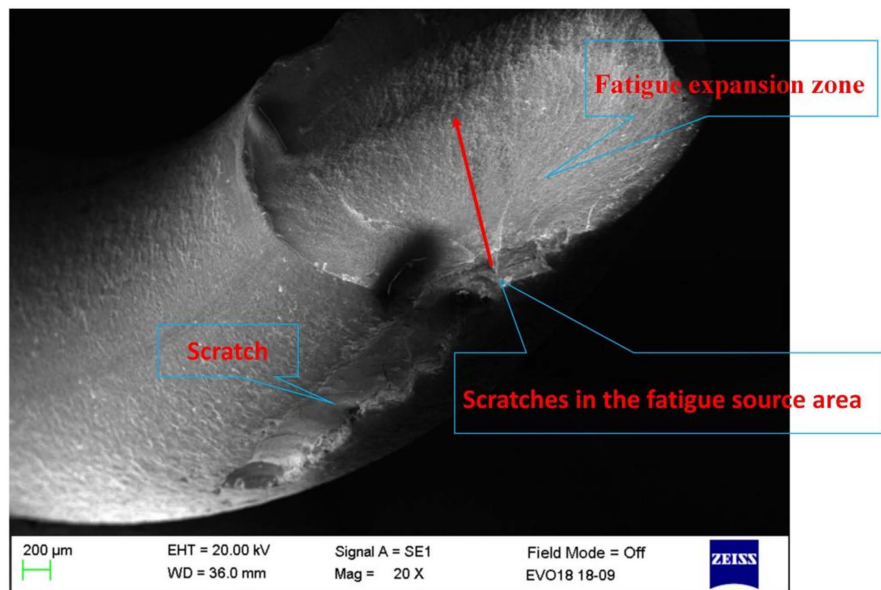
**Figure 17.** Microscopic morphology of the fatigue source area caused by spring mechanical damage fatigue fracture.



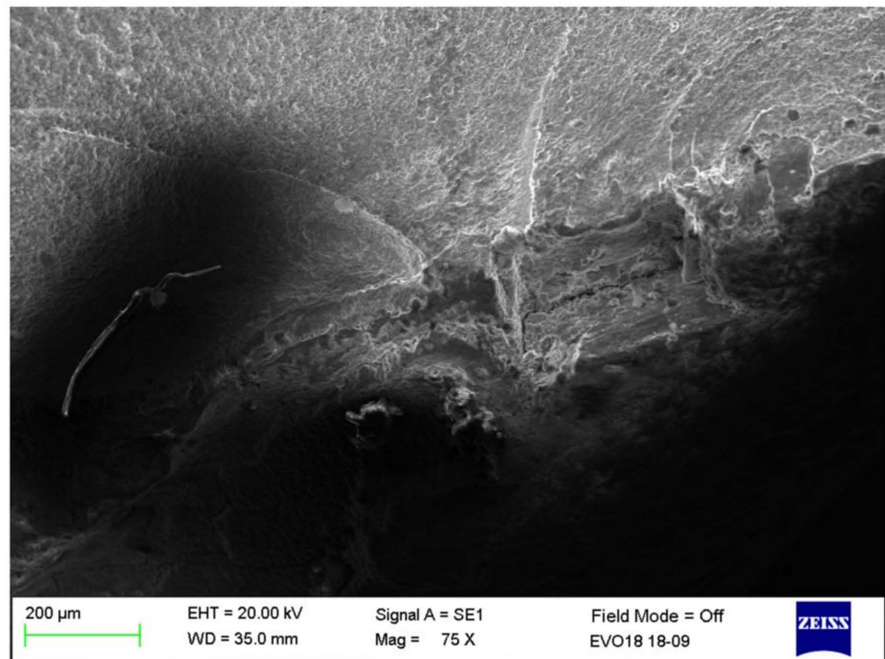
**Figure 18.** Microscopic morphology of the fatigue fracture propagation zone caused by spring mechanical damage.

#### 4.6. Fatigue Fracture Caused by Scratches

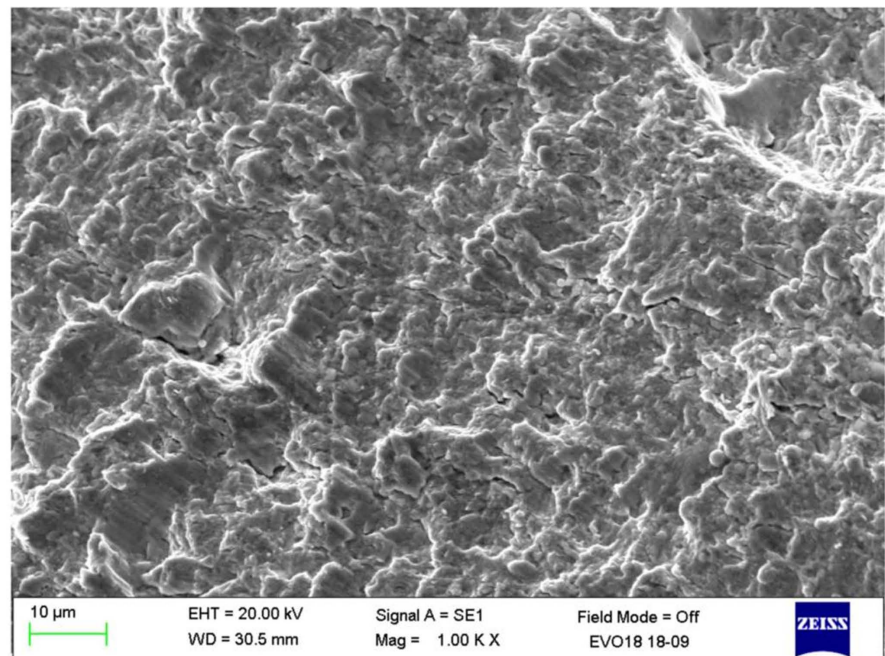
There are obvious radial fatigue propagation traces from the source area to the surrounding area under the low magnification and microscopic morphology of the spring fracture, and there are obvious long strip scratch marks at the fracture in the fatigue source area, severe oxidation, obvious fatigue glow in the fatigue expansion area, and the final fault area is mostly U-shaped, with generally ductile fractures. The fatigue fracture morphology caused by spring scratches is shown in **Figure 19**, and the microscopic morphology of the fatigue source area and fatigue expansion zone caused by spring scratches are shown in **Figure 20** and **Figure 21**.



**Figure 19.** Morphology of fatigue fracture caused by spring scratches.



**Figure 20.** Microscopic morphology of the fatigue source area caused by spring scratches.

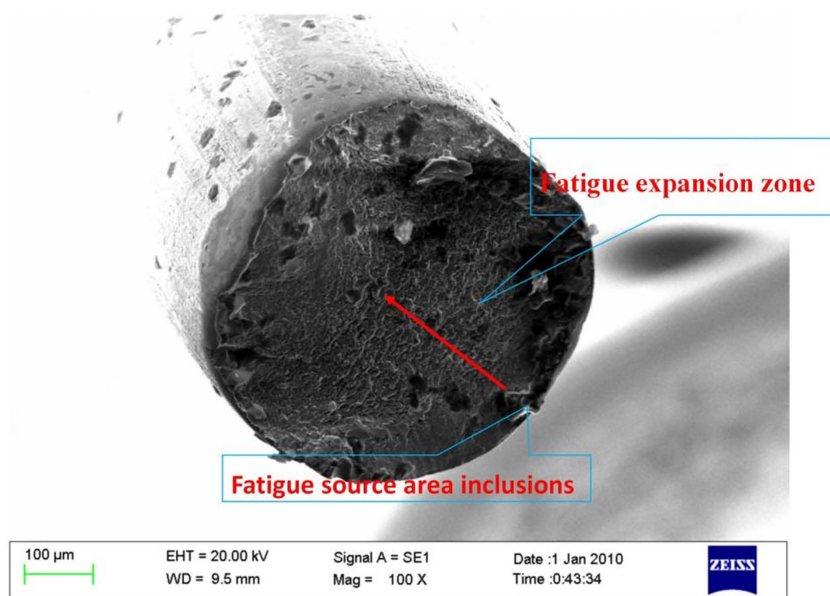


**Figure 21.** Microscopic morphology of the fatigue fracture propagation zone caused by spring scratches.

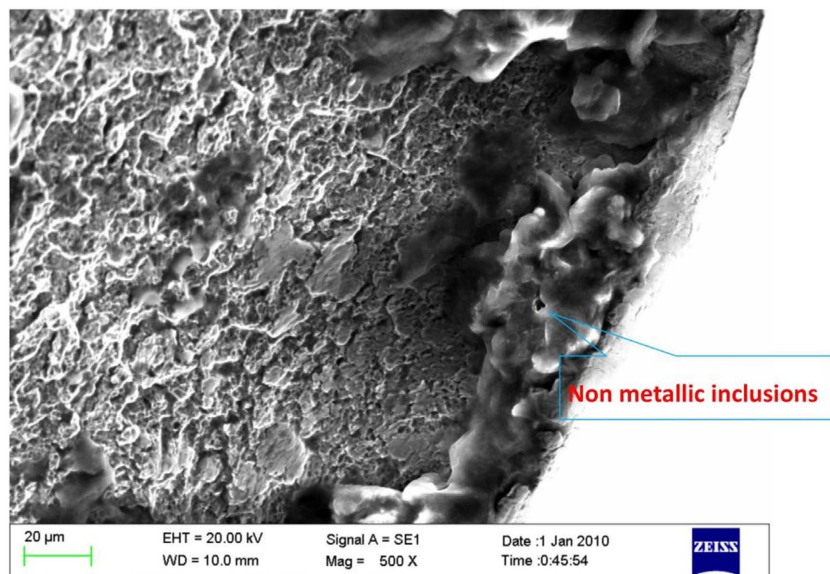
#### 4.7. Fatigue Fracture Caused by Inclusions

There are obvious traces of radial fatigue propagation from the source area to the surrounding area under the low magnification and microscopic morphology of the spring fracture, obvious non-metallic inclusions at the fracture in the fatigue source area, obvious fatigue glow pattern in the fatigue expansion area, and the

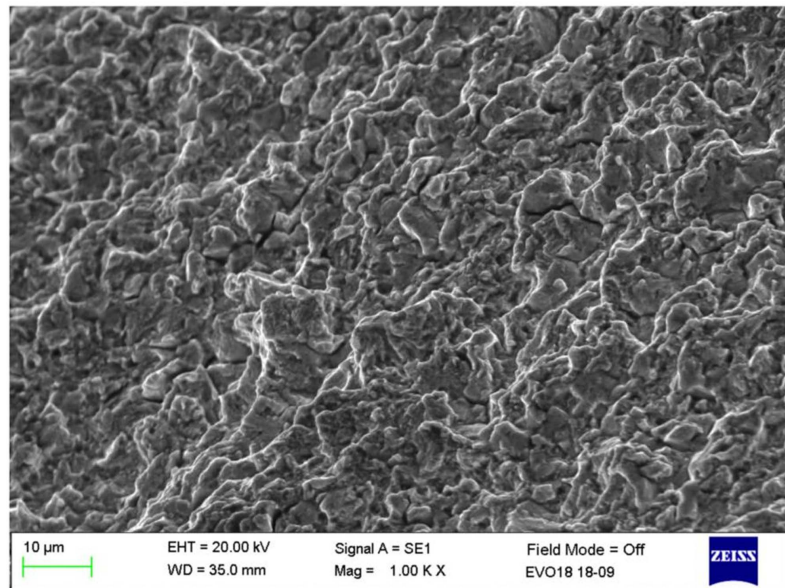
final fault area is mostly U-shaped, generally ductile fracture, the morphology of the fracture caused by spring inclusions is shown in **Figure 22**, and the microscopic morphology of the fatigue source area and expansion area caused by spring inclusions is shown in **Figure 23** and **Figure 24**. The results of electron microscopy analysis of non-metallic inclusions in the source area of spring fatigue are silicate inclusions, as shown in **Figure 25**, and the comprehensive force analysis, fracture morphology characteristics, and micro-electron microscopy spectroscopy can attribute the spring failure to the stress concentration generated by the inclusion edge, and finally, the bending-torsion composite fatigue fracture caused by the spring failure.



**Figure 22.** Morphology of fatigue fracture caused by spring inclusions.



**Figure 23.** Microscopic morphology of the fatigue source area caused by spring inclusions.



**Figure 24.** Microscopic morphology of the fatigue propagation zone caused by spring inclusions.

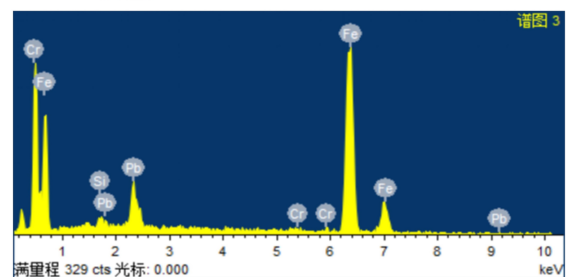
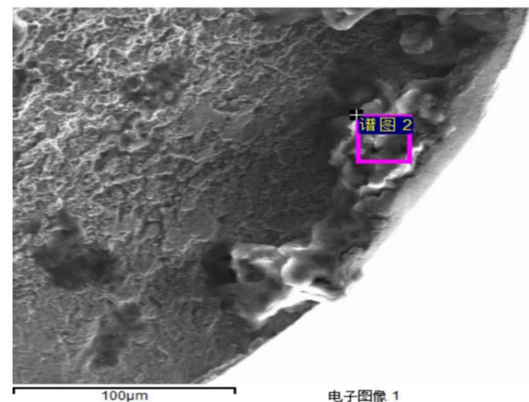
Processing Options: All Analyzed Elements (Normalized)

Number of replicates = 4

Standard samples:

O	SiO <sub>2</sub>	1-Jun-1999 12:00 AM
Na	Albite	1-Jun-1999 12:00 AM
Mg	MgO	1-Jun-1999 12:00 AM
Al	Al <sub>2</sub> O <sub>3</sub>	1-Jun-1999 12:00 AM
Si	SiO <sub>2</sub>	1-Jun-1999 12:00 AM
S	FeS <sub>2</sub>	1-Jun-1999 12:00 AM
Cl	KCl	1-Jun-1999 12:00 AM
K	MAD-10 Feldspar	1-Jun-1999 12:00 AM
Ca	Wollastonite	1-Jun-1999 12:00 AM
Fe	Fe	1-Jun-1999 12:00 AM

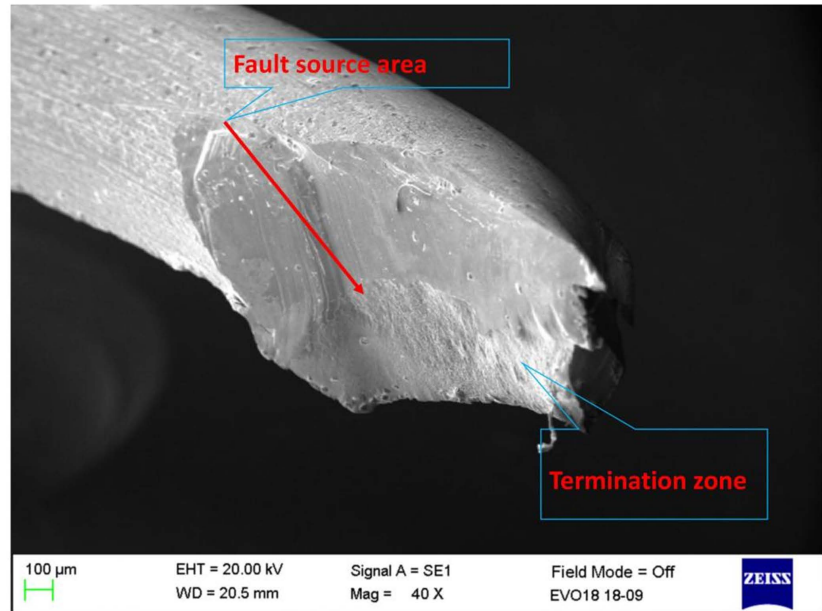
Element	Weight Percentage	Atom Percentage
O K	60.94	75.78
Na K	3.70	3.20
Mg K	2.19	1.80
Al K	3.89	2.87
Si K	8.64	6.12
S K	4.02	2.50
Cl K	4.21	2.36
K K	3.69	1.88
Ca K	2.79	1.38
Fe K	5.93	2.11
Total	100.00	



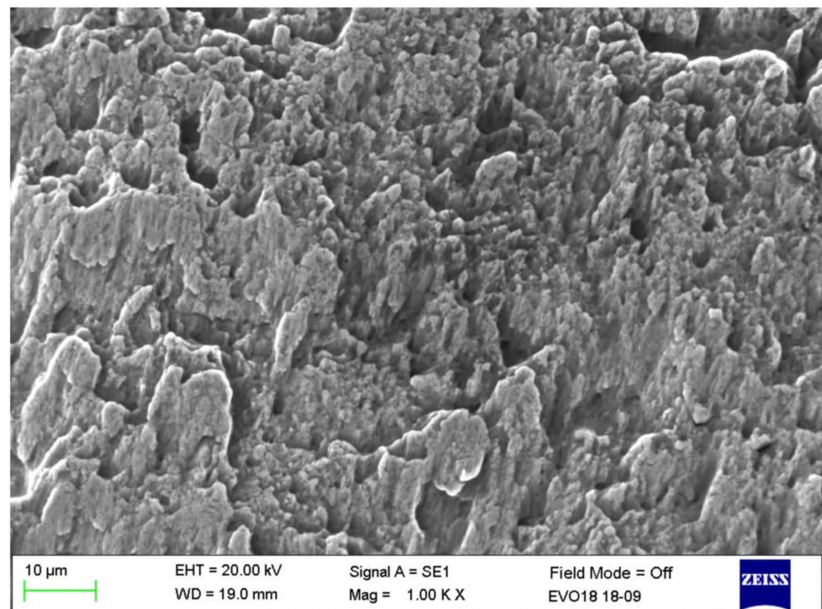
**Figure 25.** Electron microscopy analysis results of non-metallic inclusions in the fatigue source area caused by spring inclusions.

#### 4.8. External Force Damage and Fracture

The spring is affected by an abnormal shear external force, and its fracture has obvious traces of approximate parallel expansion from the source area under low magnification and microscopic morphology, and the fracture has obvious friction failure traces, and the fracture is a shear ductile fracture. The morphology of the fracture of the spring external force damage is shown in **Figure 26**, and the microscopic morphology of the fracture of the spring external force damage is shown in **Figure 27**.



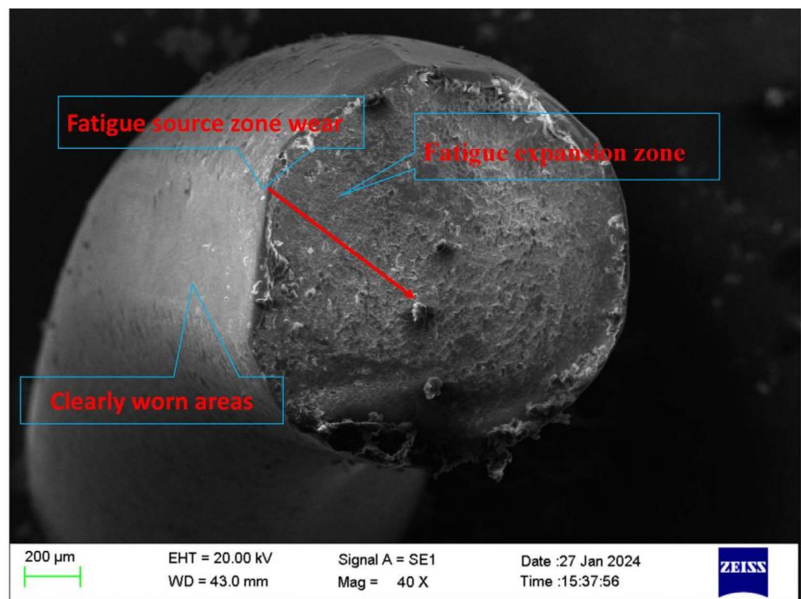
**Figure 26.** Morphology of the fracture of spring external force damage.



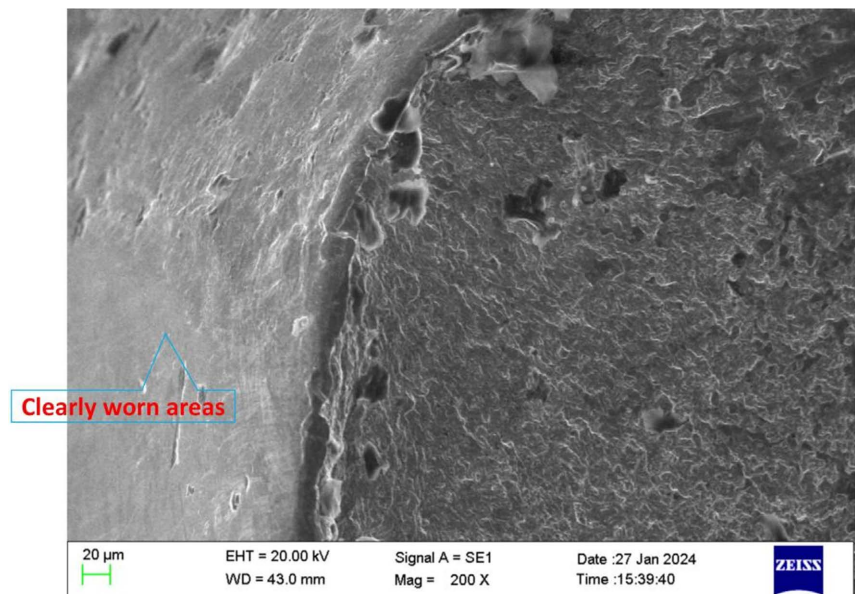
**Figure 27.** Microscopic morphology of the fracture of spring external force damage.

#### 4.9. Fatigue Fracture Caused by Wear

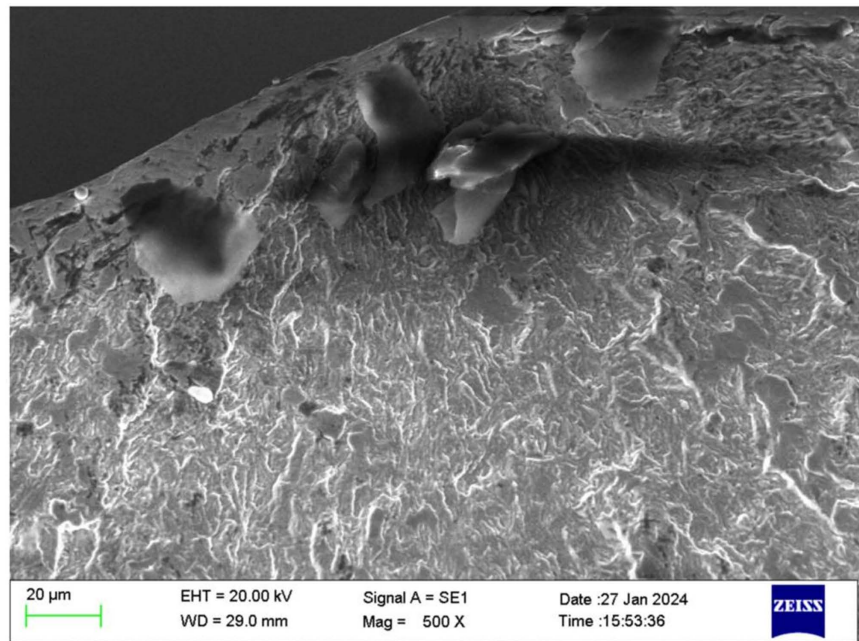
Under normal circumstances, the spring is affected by the torsional warping force of bending, and its fracture has obvious radial fatigue propagation traces from the source area to the surrounding area under low magnification and microscopic morphology. There are obvious wear marks at the fracture in the fatigue source area, and the fatigue flaring in the fatigue expansion area is obvious. The microscopic morphology of the fatigue fracture caused by spring wear is shown in **Figure 28**, and the microscopic morphology of the fatigue source area and fatigue propagation zone caused by spring wear are shown in **Figure 29** and **Figure 30**.



**Figure 28.** Morphology of fatigue fracture caused by spring wear.



**Figure 29.** Microscopic morphology of the fatigue source area caused by spring wear.



**Figure 30.** Microstructure of the fatigue propagation zone of fatigue fracture caused by spring wear.

## 5. Conclusion

Although the spring is small, the role it plays cannot be ignored. As the core component of the power system, the reliability of the spring directly affects the performance of the whole machine, and once it fails, it can sometimes cause major quality accidents. The results show that fatigue crack initiation and propagation behavior will inevitably occur under ultimate load [7] [8], and this paper clarifies the main failure characteristics of internal combustion engine springs, which can effectively distinguish quenching cracks, corrosion fatigue, and manufacturing defects. Fatigue manufacturing defects caused by surface defects, such as folding and inclusions, usually lead to early engine failure and are related to batch. Corrosion fatigue is related to the harsh service environment, due to the long-term high temperature of the spring, the corrosive medium, and the alternating stress; it is one of the main factors of failure after long-term use. Surface protection technologies such as anti-corrosion coatings can be used to control the surface quality of folds and scratches and the intrinsic quality of inclusions from the process source, and the oil can be regularly checked for deterioration and acidification under permitted conditions to prevent early failure.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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