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Research Article

Analysis of Factors Influencing the Fatigue Strength of Railway Fastening Clips

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Abstract

Presented paper characterized key factors influencing fatigue strength, including geometry, surface condition and chemical composition, as well as other parameters affecting the performance of railway fastening clips. Additionally, other technologies for improving the fatigue resistance are presented. The aim of the experimental part of the study was to evaluate the cause of the premature failure of a fastening clip during a scheduled fatigue test performed in accordance with the DBS 918 127 standard. A series of tests were conducted, including chemical composition analysis, microstructure examination, hardness testing, and fractographic analysis. Based on this research, it was concluded that the root cause of the premature failure was a particle embedded into the surface of the spring during the bending process.

Keywords: Rail fastening system; Tension clip; Fatigue strength; Cyclic load; Clip fatigue life

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Introduction

The safety and efficiency of railway operations depend on the reliability of rail fastening systems, which secure the rail to the sleepers. A key component of these systems is the elastic clip, which must withstand repeated loading cycles while ensuring a secure rail fastening (Figure 1) [1]. Throughout its service life, a railway spring is subjected to both static and dynamic loads, creating harsh operating conditions that may lead to component failure [2].

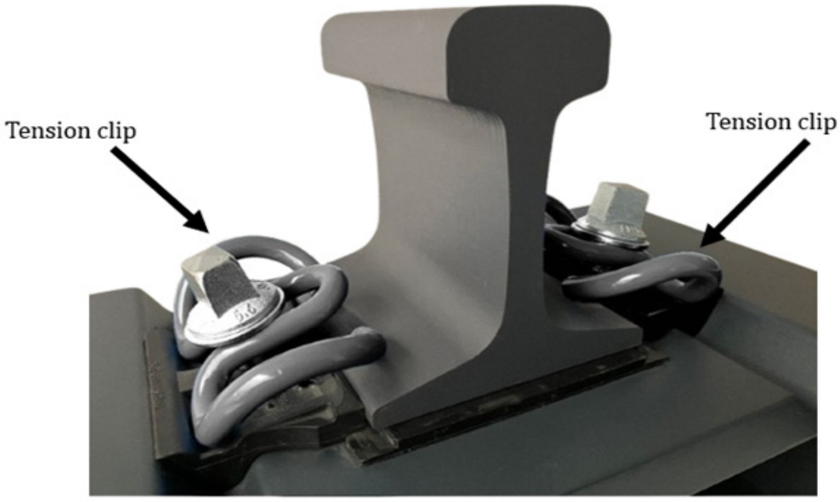

Figure 1: Railroad W14 fastening system [1].

Tension clips meet several essential requirements: they should exhibit anti-vandal characteristics [3], provide proper clamping force, appropriate elasticity parameters, and be functional for automatic installation. However, not all fastening systems, such as those using SB clips, allow for the widespread use of automated installation and rely on manual mounting, which increases labor costs and installation time.

Beyond performance considerations, the manufacturability and cost-effectiveness of clip production remain crucial factors. Achieving an optimal balance between durability, safety, and economic feasibility is essential for the development of advanced railway fastening systems.

But one of the most important parameters of tension clips is fatigue strength, as it directly influences the safety and reliability of train operations. A failure of the clip can lead to a reduction in clamping force or even a complete loss of contact with the rail in the case of both clip ends breaking off, which, in turn, can have severe consequences, including the risk of derailment. Given the significant role of fatigue strength in ensuring long-term durability, numerous studies have explored various approaches to improving the fatigue performance of railway clips [2,4-8].

To assess the durability, manufacturers perform fatigue tests in accordance with standards such as DBS 918 127 [9], which stipulate that each spring must endure 3 million cycles of loading at a predetermined amplitude to evaluate its fatigue resistance and performance under cyclic stress. However, real-world operational conditions subject the clips to significantly higher loads. Based on the findings of [2], a single fastening clip undergoes approximately 5,625,000 cycles annually, accumulating up to 28,125,000 cycles after five years and 56,250,000 cycles over a ten-year service period. Given that the endurance limit for steel under reverse bending stress typically falls within 30–60% of its ultimate tensile strength [2,6], ensuring high fatigue resistance is crucial for extending the operational lifespan of railway fasteners.

Despite the importance of fatigue strength, publicly available research on the manufacturing technology of railway clips remains limited due to industrial competition. Most scientific studies focus on failure analysis [2,4,6,8,10], environmental influences and material properties, while details regarding production methods, heat treatment processes, and surface modifications are often undisclosed. This gap in the literature highlights the need for further investigation into the optimization of manufacturing techniques to enhance the performance and longevity of railway fastening systems.

There are several directions for improving the fatigue strength of railway fasteners today, such as reduction of decarburization, controlling of the non-metallic inclusion quantity, surface treatment, geometry optimization etc.

Reduction of decarburization

In order to impart the necessary characteristics to the spring, it undergoes thermal processing, which can lead to decarburization, negatively affecting the fatigue strength of the clamp. The decarburized layer has lower strength than the base material [2,6,8,11]. According to the standard used for manufacturing clamps, decarburization is allowed up to a depth of no more than 0.2mm [9]. This standard has been criticized by some researchers. They argue that this level of decarburization can lead to the failure of the clamps [2,4,5]. They were provided a study, that concludes that the samples whose failure was caused by decarburization had a decarburization depth ranging from 0.17 to 0.36mm, which confirms that the allowable decarburization depth of 0.2mm, as per the standard, is too deep [8].

As the depth of the decarburized layer increases, the fatigue limit of the material decreases. This happens because the ΔKI generated at the crack tip increases as the depth of the decarburized layer increases, assuming that the size of the initial crack in the decarburization layer is the same as the depth of the decarburization layer [5]. Scientific studies present a graph showing the relationship between the level of decarburization and the reduction in fatigue strength. It is stated that there is a correlation, where at a decarburization level of 0.1mm and 0.2mm, fatigue strength decreases by approximately 12% and 24%, respectively [5].

The maximum allowable depth of the decarburized layer of SKL15 on the route where the survey was conducted should be equal to or less than 0.04mm, with accordance of [12]. However, the stress range at the crack location was also excessive, so the stress range should be controlled [2,7,8]. When the decarburization layer is present to an effective degree, a constant endurance limit of 325MPa is seen regardless of the material strength. This means that, due to the low strength of the decarburized layer, cracks are generated even under a low-stress range, and these cracks serve as initial cracks that propagate into the base metal [8].

Modification of spring geometry

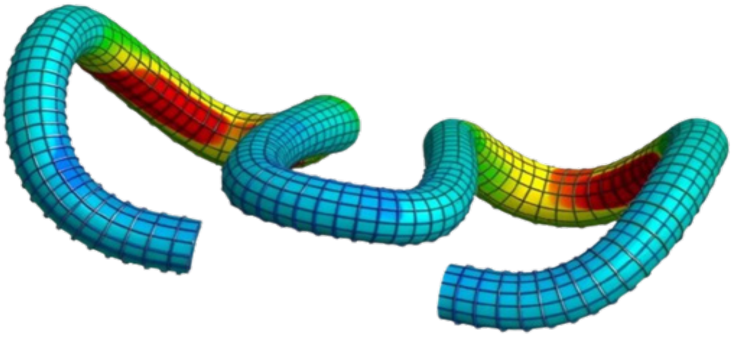

Figure 2: Stress distribution in a tension clip [3].

The geometry and surface condition of tension clips play a vital role in their fatigue strength and longevity. Sharp geometric transitions should be avoided, and all structural changes must incorporate smooth, rounded transitions to minimize stress concentrations (Figure 2) [11]. Additionally, the surface of the clip must be free from corrosion, scratches, and defects that could serve as initiation points for fatigue cracks. Any premature failure of the spring presents a direct risk to railway safety, particularly for passenger transport. Manufacturers are compelled to round the geometric changes in the spring to distribute the stresses over a larger surface area and avoid their concentration in a single location. Several studies have been conducted on this issue [3,6].

The geometry of the spring is an essential parameter that directly influences the clamping force, which is achieved through deformation during the spring installation process [13]. For most springs, the clamping force varies between 7.5kN and 12.5kN and is associated with the deformation of the nose, which ranges from 5 to 15mm [14].

Composite clamps with damping capability

Promising research has been conducted in the study of hollow springs with varying inner diameters filled with damping polymers. These polymers are designed to absorb vibrations and prevent resonance during train operation, thereby enhancing the fatigue strength of the clamps [6].

The process for filling a damping material into a hollow clamp is as follows: hollow bars with different internal and external diameters are selected, heated and forged into hollow clamps (Figure 3) [6]. During this process, it is crucial to ensure that the hollow diameter of each section of the clamp is precisely defined. Afterward, the internal hollow structure of the clamp is cleaned and adhesive is sprayed inside. When the damping material is heated to 150 °C, the inner cavity of the clamp is filled under pressure. The material then naturally dries and solidifies, resulting in an optimized clamp with high damping capability [6].

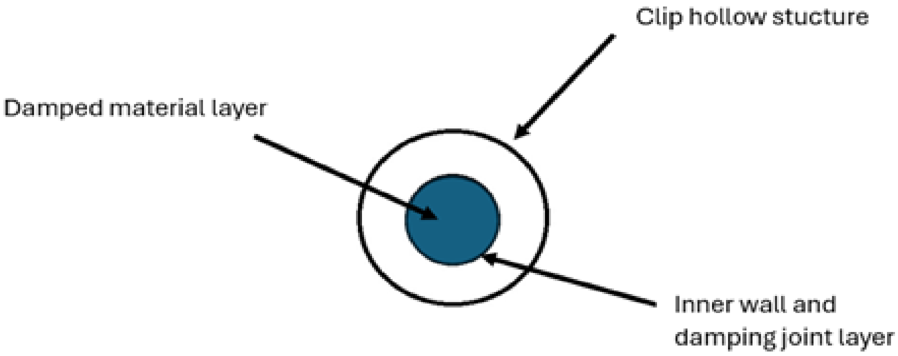

Figure 3: Composite damping clip scheme made on the base [6].

For a solid clamp with a 14mm external diameter and 0mm internal hole, hollow clamps with a 14mm external diameter and 2mm internal hole, a 14mm external diameter and 6mm internal hole and a 14mm external diameter and 8mm internal hole, the assembly clamping force of the clamp was 9.5kN, 7.6kN, 8.3kN and 9.6kN, respectively. The clamping force first decreased and then increased, while the stress variation initially increased and then decreased, with the maximum value reaching 1420MPa for the hollow structure with a 14.4mm external diameter and 2mm internal hole [6].

For the clips with an outer diameter of 14.0mm and an internal hole of 0mm, as well as for the hollow clips with outer diameters of 14.4mm (internal hole 2mm), 14.6mm (internal hole 4mm), and 14.8mm (internal hole 6mm), there is an improvement in the vibrational characteristics with an increase in both the outer and internal diameters. The second-order "butterfly" vibration frequency increases from 692Hz for the solid clip to 821Hz for the hollow clips, significantly distancing it from the excitation frequency resulting from the wheel-rail interaction at train speeds of 300–350km/h [6].

Chemical composition

The chemical composition of springs is described in the DB standard. In order to increase the fatigue strength, it is crucial to control the non-metallic inclusions present in the steel. Non-metallic inclusions in steel are chemical compounds and non-metals present within the metal matrix, arising from various sources such as slag and refractory contamination, deoxidation processes and precipitation reactions.

These inclusions are typically categorized into three primary types based on their chemical composition:

A. Sulfide Inclusions: Predominantly manganese sulfides (MnS), formed during the solidification of steel.

B. Single-Phase Oxide Inclusions: Comprising oxides like alumina (Al_2O_3) or silica (SiO_2), resulting from deoxidation practices.

C. Dual-Phase Complex Oxide Inclusions: Consisting of combinations of oxides, such as spinels or silicates, which form through complex reactions during steel processing.

The presence of these non-metallic inclusions significantly impacts the fatigue strength of spring steels. Their diverse compositions and morphologies disrupt the homogeneity of the steel matrix, leading to stress concentration points that can initiate fatigue cracks. This detrimental effect is particularly pronounced in high-strength steels, where inclusions can markedly reduce fatigue performance. Studies have demonstrated that non-metallic inclusions not only lower the fatigue strength but also introduce considerable variability in fatigue life, underscoring the critical need for stringent control of inclusion characteristics to enhance the reliability and performance of spring steels [11].

While sulfides, which are deformable inclusions, slightly reduce fatigue strength, oxides, such as aluminium oxide, are non-deformable inclusions. These non-deformable inclusions have a more significant negative impact on fatigue strength [11].

Plastic forming process-bending process

There are numerous studies describing the surface condition and fatigue strength of various products, including springs and leaf springs. Surface defects, including decarburization, as well as the presence of laps, seams, and other imperfections, lead to premature spring failure (Figure 4). A key aspect of this process is the surface quality of the worked component, as any tool marks left during processing can act as stress concentrators. Such micro-scratches and surface irregularities weaken the material structure, increasing the risk of fatigue cracks and reducing the component’s service life. Therefore, proper selection of tools, their technical condition, and precise control of process parameters are crucial to minimizing the risk of surface defects. To address these issues, a grinding or draw-peeling (shaving) process of the outer layer of spring wire is used to improve its quality [11,15].

Figure 4: Bending marks on the surface of clip [1].

Shot peening

Surface treatment is widely employed in the production of automotive springs to enhance their durability, with shot peening being one of the most effective methods. This process introduces compressive residual stresses on the surface, significantly improving fatigue strength. In suspension spring manufacturing, a double-shot peening process is often required to ensure both optimal compressive stress distribution and refinement of the surface microstructure [4,12,16].

Shot peening can reduce the impact of surface defects that negatively affect the fatigue properties of components. These defects may arise from manufacturing processes such as machining or develop during service due to foreign object damage [17]. Shot peening enhances fatigue resistance by introducing compressive residual stresses that prevent crack propagation. The improvement in fatigue strength is primarily due to macroscopic residual stress, surface finish and structural modifications, influenced by the initial microstructure, strengthening method and applied stress. Higher residual stress and deeper plastic deformation reduce stress relaxation during cyclic loading. However, overestimating residual stress effects without considering structural changes can be misleading. While excessive shot peening may damage low-strength materials, compressive residual stresses generally counteract these effects [12]. Despite its proven effectiveness, shot peening is not yet widely adopted in the production of railway fastening clips. Incorporating this technique could significantly enhance the durability of railway fastening systems, reducing fatigue-related failures and improving overall railway safety and reliability.

Taking in to account several factors (most mentioned above) that influence the fatigue strength of railway fastening clips the aim of research part of the study was to evaluate the root cause of premature failure of this part during the tests.

Materials and Methods

The object of the research was the SKL 14 railway fastening clip, which failed during testing significantly faster than required. During the fatigue strength testing, the sample must withstand 3 million repetitive load cycles, according to the DBS 918 127 [9]. The fatigue testing parameters for the tested railway fasten are present in Table 1. During the scheduled fatigue strength test of the SKL 14 clamp, premature failure of the spring occurred. The spring broke after 700,000 cycles, which is a rare and negative result (Figure 5). Additionally, 2 samples without this type of embended particle was tested and the result is positive.

Table 1: The fatigue testing parameters for the clip.

Test Parameters		
Amplitude (peak to peak) [mm]	Frequency [Hz]	Vibration start position [mm]
2.00	18	10.9

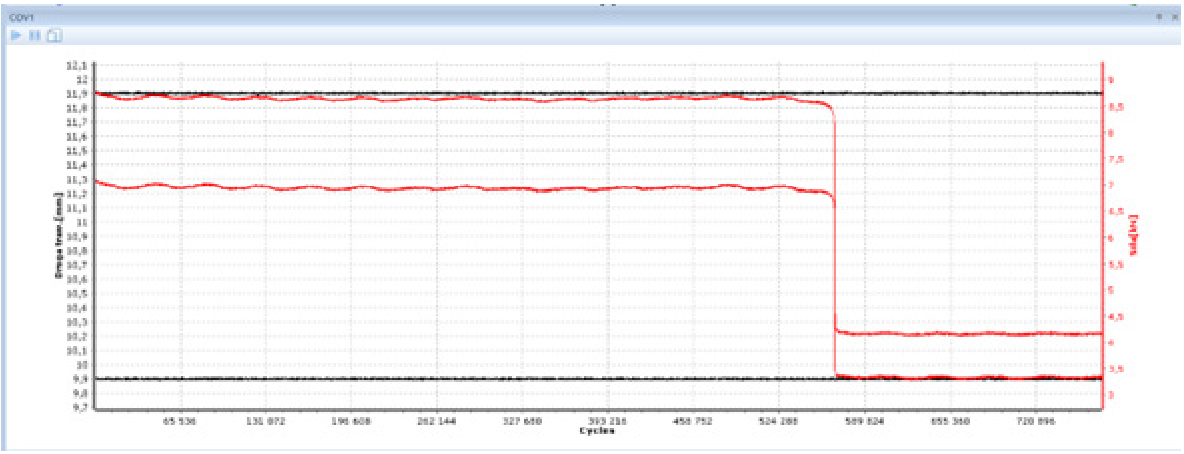

Figure 5: The screen of the Fatigue test graph of the SKL clip.

To evaluate the cause of the failure, a series of investigations were conducted, including fractographic analysis, decarburization analysis, microstructure examination, and hardness testing of the sample and chemical composition of the material.

The clamping force and fatigue test was conducted using a Labortech Lab-test 6.50H.5.00.0 - TS fatigue testing machine. The test was carried out in accordance with the DBS 918 127 standard [9]. The graph presents two curves representing the upper and lower amplitude positions, along with the corresponding forces at the peak and trough of a 2mm peak-to-peak amplitude. The fatigue test setup consists of a fatigue testing machine, a metal profile simulating a sleeper, and a WFP12K12 angle plate. The traverse is placed at the bottom and has an end that simulates the sleeper. The test setup fully replicates the railway system (Figure 6).

Figure 6: SKL14 fatigue test setup [1].

For the hardness test, the sample was cut from the end of the clip arm and polished using belt grinder machine with 80SiC sandpaper. The hardness test was conducted using a Mitutoyo HV-100 hardness testing machine by the DIN EN ISO 6507-1 standard.

The chemical composition test was conducted using a Bruker AXS machine. The test was performed on a wire from the same batch number. Samples were cut using a saw with water cooling and then polished using a Fluxana Grinder MLG11.

Microstructure analysis was performed on the cut from the sample, that was cut near the fracture using a Motic BA310 MET-H Trinocular optical microscope. Fractographic analysis was carried out using a stereoscopic microscope ZEISS and a magnifying glass with 40x magnification.

Results and Discussion

The clamping force parameter meets the standard requirements and indirectly indicates that the heat treatment and other key parameters of the spring manufacturing process are satisfactory. The clamping force test results are present in Table 2.

Table 2: The clamping force test results.

Clamping Force after 1 Cycle kN	Clamping Force after 10 Cycle kN
11,4	9,5

In the analyzed case, the chemical composition met the requirements of the DBS 918 127 standard (Table 3). The hardness of the clamps is specified in the standard and should be within the range of 400–460HV. The test was conducted on different parts of the prepared sample from the edge to the centre, and showed an average result of 450HV. The hardness values obtained during testing were consistent with the specified range, confirming that the material hardness meets the required criteria.

Table 3: The chemical composition test result.

Wt. %	C	Si	Mn	P	S
According to the Standard: EN 10089-2002	0.35 - 0.42	1.5 - 1.8	0.5 - 0.8	max 0.025	max 0.025
Internal laboratory result	0.3778	1.6411	0.6501	0.0091	0.0047

The content of non-metallic inclusions meets the requirements of DBS 918 127 standard (Figure 7).

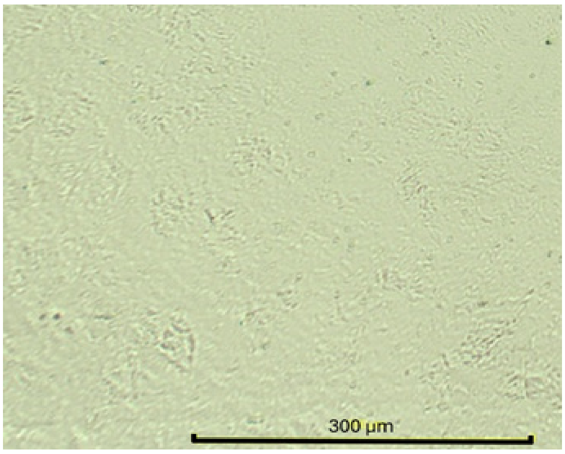

Figure 7: Unetched polished section for evaluating non-metallic inclusions, (100x magnification).

Observation of the microstructure of investigated railway fastening clip revealed (magnification x100) a clear and uniform structure, consistent with the tempered sorbite phase, without any significant irregularities or deviations from the standard (Figure 8).

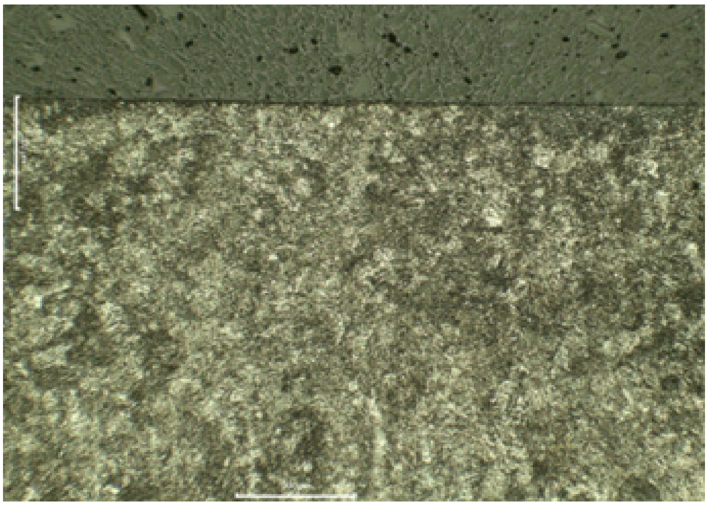

Figure 8: The microstructure of the surface layer of tested railway fastening clip, etched with nitride solid solution (magnification x100).

No decarburization was observed on the surface of the sample, which could have potentially served as a source for crack initiation and premature failure, as described in the introduction.

The macroscopic observation of the fracture surface reveals three distinct zones (Figure 9):

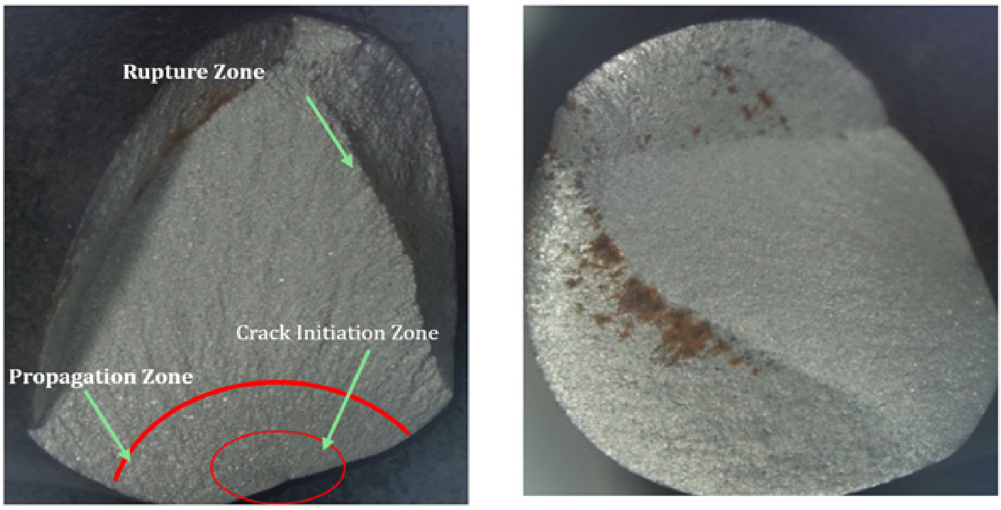

Figure 9: The fracture images of tested railway fastening clip using a stereoscopic microscope, revealing the distinct zones of failure.

a) Crack Initiation Zone: Located at a stress concentration point, it shows small, irregular markings or dimples, indicating the start of fatigue damage.

b) Propagation Zone: Characterized by smooth, elongated patterns, it shows the crack growing progressively under cyclic loading.

c) Rupture Zone: The final fracture area, with coarse, jagged edges, where the material fails completely under the final load.

During the fractographic analysis with a magnifying glass, a protrusion was found at the crack initiation site (Figure 10), as well as a "tongue" in the failure initiation zone. This "tongue" is a hard particle that was embedded into the surface of the spring during the bending process. The fatigue failure of the component began precisely from this embedded particle.

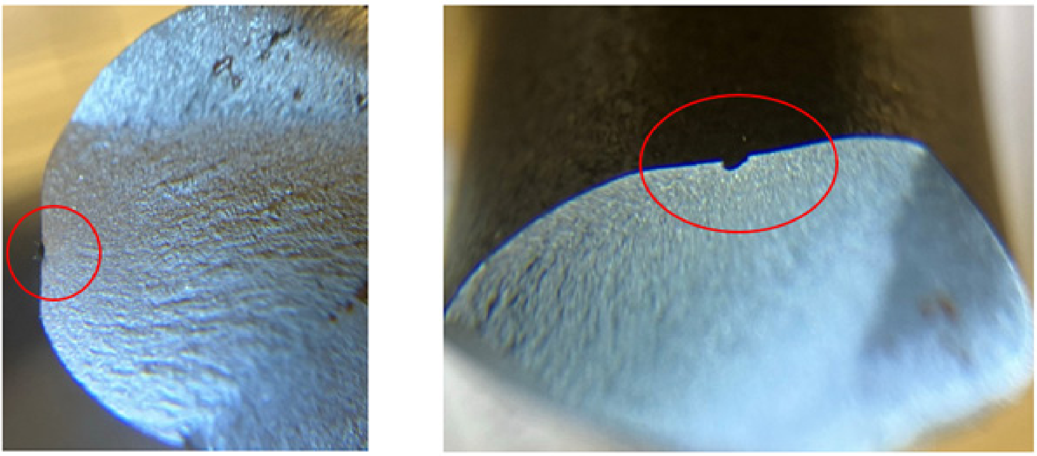

Figure 10: The fracture images of tested railway fastening clip performed using a loupe with a magnification of 40x.

Due to the inability to analyse the chemical composition of this particle, its exact nature remains unclear. However, since it is located in an area where the spring is deformed due to bending, it can be assumed that this particle was embedded into the surface of the spring during the bending process. This, in turn, acted as a stress concentrator and caused the premature failure of the component.

Conclusion

Taking into account many factors such as clamping force, hardness, chemical composition, fracture analise the tested railway fastening clip was characterized by:

A. Hardness is within the tolerances of the standard.

B. Appropriate chemical composition to the standard of the steel.

C. Appropriate microstructure as is as expected after hardening and tempering and no deviations from the standard were found.

Performed investigation showed that, the cause of premature failure of the tested clip was hard particle in the surface layer reviled during the fractographic analysis. This particle served as a stress concentrator, leading to the premature failure of the component. It was likely pressed in during the bending process. Additionally, two samples without this type of embedded particle were tested, and the results were good.

Ensuring high fatigue strength of components plays a key role in their reliability and durability. Although cases of reduced fatigue strength are rare, it is important to consistently consider the chemical composition, microstructure, hardness, and other parameters of the clamp, as well as processing conditions. The quality of bending, coiling and other deformation processes directly affects the material's structure, mechanical properties, and resistance to fatigue failure. Optimizing these factors helps minimize the risk of defects, extend the service life of components, and ensure their stable performance under demanding operating conditions.

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Conflict of Interest

The author declares no conflict of interest, as the work was carried out as part of the responsibilities of the primary position, without receiving any additional compensation.

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