

Article

Residual Stresses and the Microstructure of Modeled Laser-Hardened Railway Axle Seats under Fatigue

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Abstract: Railway wheels are usually attached to axles by press-fitting; therefore, the mechanical processes taking place during operation can result in failure, with fatal consequences for the axle seats. This manuscript describes the effect of laser hardening on the residual stress state, microstructural parameters (lattice defects—dislocations, crystallites, microstrains, etc.), and mechanical properties of laser-hardened EA1N steel railway axles under fatigue life conditions. Differences were found between ground, single-track, and multi-track hardened surfaces. Tensile residual stresses, low dislocation densities and hardnesses, and different microstructures (tempered cubic martensite) were found at the overlapped tracks and at the boundary of the heat-affected zone and bulk surface compared with the hardened zone. As a result, the surface treatment of axle seats by laser hardening improved the fatigue failure resistance compared with untreated seats. Optimal properties of the integrity of the axle seat surface were achieved, including fatigue resistance, which seems to be positively influenced mainly by sufficient hardness and the appropriate microstructure. The influence of the other investigated parameters was not evident, and was reduced by the presence of fretting corrosion and press-fitting.

Keywords: railway axle seats; EA1N steel; laser hardening; X-ray diffraction; fatigue; residual stresses; microstructural parameters; hardness



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1. Introduction

Railways are by far the safest, most reliable, cheapest, and the most environmentally friendly land transportation method. One of the problems with rail transport is the mechanical components (e.g., axles and wheels) that could fail. Wheels are usually connected to axles by press-fitting, and thus failure with fatal consequences can occur on the axle seats due to ongoing mechanical processes during operation. Therefore, railway axles are tested at dynamic loading, considering a working life of about 30 years (i.e., 10^9 cycles) [1]. In the 1970s, the Union Internationale des Chemins de fer (UIC, International Union of Railways) developed the UIC 811-1 standard [2], recommending EA1N and EA4T steels for railway axles throughout Europe. These carbon steels have a ferritic–pearlitic microstructure with a yield strength of 330 MPa and ultimate strength of 600 MPa for EA1N steel [3]. The European Committee for Standardization (CEN) then approved EN13103 [4], EN13104 [5], and EN13261 for the design in 2008. The up-to-date standards include limits for surface integrity parameters such as the hardness, residual stresses, and microstructure of surface and subsurface areas. Several contemporary methods are used to modify critical areas of the axle, e.g., hardening, laser shock peening, rolling, shot peening, etc. [6–8].

Laser hardening is becoming a well-known manufacturing process in various industries, including the automotive and railway sectors. When comparing laser hardening

technology with traditional hardening processes such as induction or flame hardening, complex shapes can be processed with a minimal heat-affected zone [9]. In addition, the interest in this process lies in the possibility of directly integrating a laser heat source on the production line without additional quenching media, as well as the ability to produce a variety of microstructures with very precise control between the soft core and the hard surface with compressive residual stresses [10,11].

In the case of local hardening, single-track hardening is sufficient. For single-track laser hardening, the compressive residual stresses are usually described on the surface in the center of the hardened area. On the other hand, the unhardened machined surface could reach very high tensile residual stresses [12]. This zone, exhibiting significant changes in residual stresses, microstructure, and hardness (which could be even lower than the base material [13]) is usually an area of potential surface crack initialization [14].

On the other hand, if a large area needs to be hardened, multi-track hardening is required. Using multi-track laser hardening with overlapping, the part of the hardened zone is re-hardened. Therefore, different zones are formed in and near the overlapped zone [15]; see Figure 1. The tempered and re-hardened zones are usually accompanied by a decrease in hardness [10,14]. In the presence of other undesirable values of surface integrity, particularly microstructural notches and tensile residual stresses, these zones are typical areas of the initialization of surface cracks [12,16].

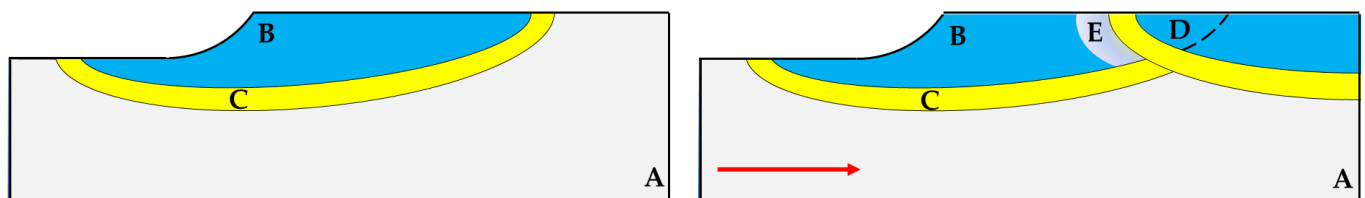


Figure 1. Schematic drawing of zones generated by single (**left**) and multi-track (**right**) laser hardening with overlapping, where the red arrow denotes the order of track laying: (A) unhardened, (B) laser-hardened, (C) partially hardened—heat-affected, (D) re-hardened—overlapped, and (E) tempered zone.

Putatunda et al. [17] compared several conventional techniques such as shot peening, carbonitriding, and induction hardening with laser hardening. It was found that induction and laser hardening yielded the largest improvement in the high-cycle fatigue strength. Simunek et al. [18] dealt with the analytical and numerical analysis of the crack growth of railway axle samples. Numerical analyses were performed to consider the residual stress state and its effect on crack propagation by different options. Considering the distribution of residual stress in depth within the residual lifetime assessment, the deviation from the most conservative experiment was reduced from 48% to 2%. Therefore, the influence of residual stresses on the effective crack growth rate was pronounced. Fajkoš et al. focused on the fatigue limit of induction-hardened railway axles made of EA4T steel in their study [19]. The increase of almost 200% in strength after heat treatment simulating induction hardening was accompanied by an increase of up to 70% in fatigue strength and only a 20% increase in notch sensitivity. Gao et al. [20] investigated the influence of induction hardening on the damage tolerance of EA4T railway axles. The damage modes of two kinds of samples were analyzed and the resultant loading capacity debit was evaluated. The fatigue strength of the smooth hardened sample was improved by 61% in comparison with that of the untreated sample. As a result of the compressive residual stresses of the induction-hardened samples, the fatigue strength of the damaged hardened sample was markedly larger than that observed for a similar defect size. Last but not least, Gao et al. [21] provided more complex research on the failure causes and hardening techniques of railway axles. It was found that fretting at the inner edge of the axle seat after pressing was unavoidable, but applying hardening could relieve the detrimental effect. The positive effect of the presence of compressive residual stresses on crack initialization was also thoroughly described.

Press-fitted joints between the wheels and axle seats are critical points of the initiation of fatigue damage [22]; therefore, it is necessary to verify how surface laser hardening affects the fatigue resistance of wheel seats in comparison with standard untreated surfaces. An experiment was designed where the entire axle seat was laser-hardened and only the most critical area, the inner edge of the axle seat, was hardened to simplify and cheapen production. As has been shown, the surface treatment of axles using laser hardening improves resistance to fatigue failure. However, the question arises as to how these optimized characteristics (suitable microstructure, sufficient hardness, and compressive residual stresses) will behave in service; therefore, the modeled laser-hardened railway axles were investigated during high-cycle fatigue tests. Therefore, the effect of surface treatment technology on railway axle seats by laser hardening to increase fatigue damage resistance and validation to model railway non-powered axles is described in this manuscript.

2. Materials and Methods

For experimental tests, a 1:3 axle model forged from EA1N [23] steel was used; the chemical composition is detailed in Table 1. The diameter of the model axle shaft was $d = 59$ mm and the seat diameter was $D = 63$ mm; therefore, the ratio was $D/d = 1.07$. This low D/d ratio provided an opportunity to test the laser-hardened seat of the model axles. For a conventional axle, this ratio is about 1.18. Notably, the scale effect is always present in fatigue tests, but is known to be more pronounced in very small samples. The scale effect will not be as severe for the medium-sized samples used (1:3 models), i.e., those over 20 mm in diameter [24]. Three samples were prepared with different surface treatments after grinding: untreated/unhardened, with single- and multi-track laser hardening. The laser hardening was carried out circumferentially, with a controlled hardening temperature (Table 2), where P , v , T , and λ are the laser power, the hardening speed (rotation speed of the rod), the hardening temperature, and the laser wavelength, respectively. LaserLine 6000 apparatus (LaserLine GmbH, Koblenz, Germany) with a KUKA KR16 robot arm (KUKA AG, Augsburg, Germany) was used for the hardening, as performed by the MATEX PM, s.r.o. company. The area of the inner edge of the axle seat (side of the axle shaft) was analyzed, as depicted in Figure 2. A technical drawing of the test samples is shown in Figure 3.

Table 1. Chemical composition of EA1N steel, data from Ref. [23].

Element	Fe	C	Mn	Si	P	S	Cr, Ni	V	Mo
Weight fraction (wt.%)	bal.	0.4	1.2	0.5	0.02	0.02	0.3	0.06	0.08

Table 2. Hardening parameters.

P (W)	v (mm·s ^{−1})	T (°C)	Mode	Track Overlapping (mm)	Beam Quality (mm·mrad)	λ (nm)	Spot Size (mm)
6000	3	1150	cont.	5	6	1060–1100	30 × 7



Figure 2. Axle models with single-track (up) and multi-track (down) laser hardening.

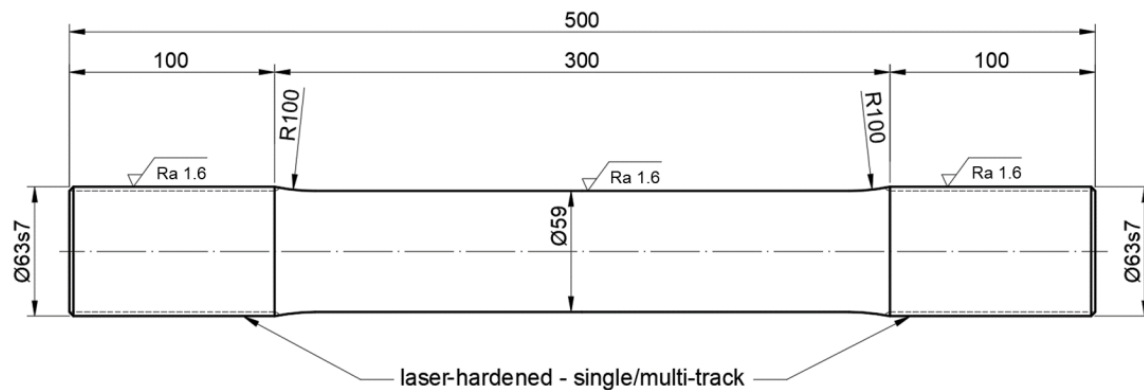


Figure 3. Technical drawing of the axle models.

The seat of the model axles was housed by press-fitting in special flanges that were clamped by bolts to the body of the test rig. Pressing of the model axles was carried out on a Schneck ZD 100 servo-hydraulic test rig (SCHENCK RoTec GmbH, Darmstadt, Germany) with a capacity of 1000 kN, as illustrated in Figure 4. Force and displacement were recorded for each model axle since these are critical parameters necessary for the reliable strength of the pressed joint. The relationship between the maximum press-fitting force achieved and the offset of the axle seat and flange diameters is shown in Figure 5. As the radial offset increases, the fitting force also increases, but it is important that even for laser-hardened axles, there is no significant dispersion. The fitting force is determined by the standard in the production of real axles.



Figure 4. Flanges press-fitting of multi-track laser-hardened axle model.

2.1. Metallography

Samples for metallographic analysis were taken from the laser-hardened seat of the model axles. The samples were oriented in such a way that the metallographic section crossed the laser track. The sampling was performed with a band saw with sufficient cooling to avoid thermal impacts on the laser track. The metallographic samples were hot-embedded into conductive Bakelite resin with carbon filler and prepared by machine grinding and polishing. The structure was induced by etching in 2% Nital (98 mL ethanol + 2 mL HNO₃). The analysis was performed on a Zeiss Axio Observer light microscope (Carl Zeiss Microscopy GmbH, Berlin, Germany).

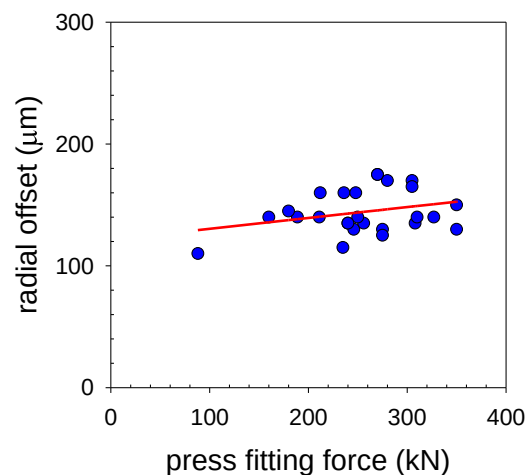


Figure 5. Press-fitting force as a function of radial offset.

2.2. Hardness

The metallographic samples were subsequently used for hardness measurements in the subsurface layer. Hardness measurements were performed 0.1 mm beneath the surface with a Qness 30 CHD Master+ hardness tester (ATM Qness GmbH, Golling, Austria) according to ISO 9015-1 [25] at a load of 9.807 N (HV1).

2.3. High-Cycle Fatigue Tests (HCF)

Rotational bending fatigue tests were performed on a Schneck UMBI 750 test rig (Carl Schenck Maschinenfabrik GmbH, Darmstadt, Germany). This is a unique lever system capable of testing 1:3 axle models up to a bending moment of 7357 kN·m. Fatigue tests were performed according to the ISO 1143 standard [26] at constant bending stress. The test rig enabled testing at a frequency of 25 Hz (1500 rpm) and an alternating load mode of $R = -1$.

2.4. Fractography

All fatigue model axles were disassembled using a Schneck ZD 100 servo-hydraulic test rig (SCHENCK RoTec GmbH, Darmstadt, Germany). Before the pressing process started, the space between the axle seat and the flange was pressurized with 300 bar oil, which facilitated the disassembly of the press fit without causing significant damage to both surfaces. The model axle seats were subsequently visually inspected using an Olympus SZ-61 stereomicroscope and a Zeiss EVO MA10 electron microscope (Carl Zeiss Microscopy GmbH, Berlin, Germany). To highlight the cracks, magnetic particle inspection was applied to the surface of the model axle seats.

2.5. X-ray Diffraction

X-ray diffraction (XRD) analyses were performed in the direction parallel to the axial axis of the axle, i.e., perpendicular to the laser-hardened tracks, as shown in Figure 2. This direction of the axle is more important from a technological point of view (direction of maximum fatigue load).

Generally, to quantify microstructural features, both morphological and material properties must be characterized, i.e., information about different phases of variable shape, size, and distribution (grains, precipitates, dendrites, pores, etc.). XRD microstructural parameters include lattice defects (dislocations), crystallites, microstrains, etc. [27]. The microstructural parameters and the state of the residual stresses on the surface were investigated.

Notably, XRD is not able to directly distinguish ferrite, bainite, and martensite phases from each other in low-carbon steels because of the small tetragonality of the crystal lattice, i.e., the splitting of the diffraction maxima is indistinguishable. Therefore, when “ferrite” is

mentioned in the text in connection with XRD, ferrite and/or bainite and/or martensite are meant.

In view of the other results, it is necessary to distinguish between the terms “grain” and “crystallite”. A crystallite is considered a domain that has a nearly single-crystal structure with minimum defects, the so-called coherently diffracting domain. It is evident that a grain, where the spatial orientations of its individual parts may differ by several degrees, is not the same as a crystallite. Therefore, a grain consists of many randomly rotated crystallites. Microdeformation (or microscopic stresses, according to Hooke’s law) is caused by the inhomogeneous distribution of elasto-plastic strain on the crystallite scale and is homogeneous within the crystallite size [28].

2.5.1. Microstructural Parameters

The X’Pert PRO MPD diffractometer (Malvern Panalytical B.V., Almelo, The Netherlands) with cobalt radiation was used to obtain X-ray diffraction (XRD) patterns. The crystallite size and microstrain were determined from these patterns using the Rietveld refinement performed in MStruct software (version 2019, Charles University in Prague, Prague, Czech Republic) [29]. The irradiated volume was defined by the experimental Bragg–Brentano geometry of the diffractometer, the effective penetration depth of the X-ray radiation (approx. 10 μm), and the pinhole size ($4 \times 0.25 \text{ mm}$). The dislocation density was calculated according to the Williamson and Smallman method [30]. The presented errors follow from the Rietveld refinement method.

2.5.2. Residual Stresses

Macroscopic residual stresses (RSs) were described using X-ray diffraction with an X’Pert PRO MPD diffractometer (Malvern Panalytical B.V., Almelo, The Netherlands) with chromium radiation. The surface RS values were calculated from the lattice deformations, which were determined based on the experimental dependencies of $2\theta(\sin^2\psi)$ assuming a biaxial state of RS, where θ is the Bragg angle, and ψ is the angle between the sample surface and the diffracting lattice planes [31]. Rachinger’s method was used to separate the $K\alpha_1$ and $K\alpha_2$ diffraction lines of the planes $\{211\}$ of the ferrite phase; the positions of the $K\alpha_1$ diffraction lines were obtained by fitting by the Pearson VII function. The X-ray elastic constants $s_1 = -1.25 \text{ TPa}^{-1}$, $\frac{1}{2}s_2 = 5.76 \text{ TPa}^{-1}$ and the Winholtz and Cohen method were used for the RS calculation. The irradiated volume was defined by the experimental Bragg–Brentano geometry of the diffractometer, the effective penetration depth of the X-ray radiation (approx. 5 μm), and the pinhole size ($4 \times 0.25 \text{ mm}$). The presented errors follow from the least-square method (non-linearity of the $2\theta(\sin^2\psi)$ function).

3. Results and Discussions

Standard tests (metallography and hardness) were supplemented by fatigue tests and fracture mechanics. These results were compared with non-destructive X-ray diffraction. This comprehensive study provided an extensive description not only of the hardened surface itself, but also of the properties of the axle models as a whole.

3.1. Metallography

As illustrated in Figure 6, the macrostructure exhibits distinct characteristics of the two laser tracks. Noteworthy is the considerable depth of approximately 1.5 mm within the laser-hardened tracks. Delving deeper into the hardened zone, optical analysis reveals subtle disparities in carbon distribution. Figure 7 presents a closer examination of the microstructural features in the individual observed areas.

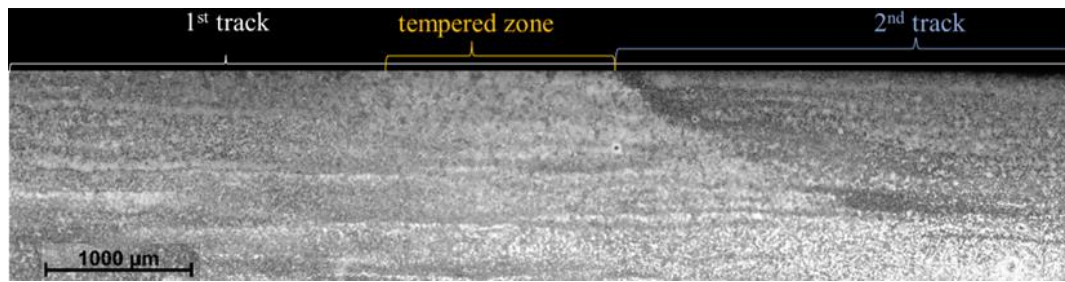


Figure 6. Macrostructure image of laser-hardened tracks, overlapped, and tempered zones.

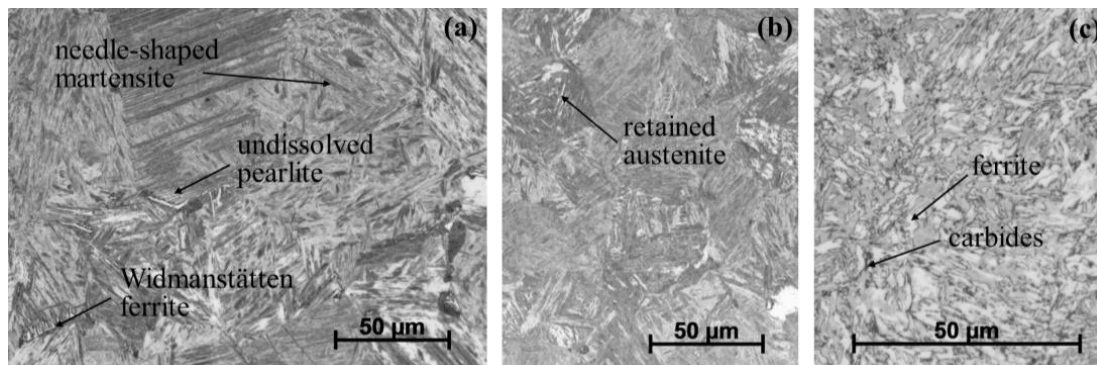


Figure 7. Microstructures of (a) laser-hardened track, (b) tempered, and (c) overlapped zones.

Within the laser-hardened track, a prevalent needle-shaped martensitic structure is evident, occasionally interlaced with undissolved pearlite or Widmanstätten ferrite. In particular, martensitic grains occasionally exhibit significant size, due to the larger grains of pearlite in the parent material. In contrast, the tempered zone displays tempered cubic martensite along with a reduced proportion of retained austenite. Of particular interest is the observation at the commencement of the second laser layer, where the structure undergoes re-hardening in the overlapped zone. Here, a notable dissolution of the martensitic structure is observed, giving rise to a fusion of ferrite and complex carbides, marking a distinct transformation.

3.2. Hardness

The trend in hardness for the single and multi-track model axle is shown in Figure 8. Notably, the hardness of the multi-track sample is slightly higher compared with the single-track sample. A scatter of values can be noticed for both samples, which is probably due to the non-homogeneous dissolution of carbon, as already stated in the metallographic analysis.

For the single-track sample, a uniform hardness above 500 HV1 can be observed throughout the width of the hardened track. At the end of the laser track, a very sharp drop to values below 200 HV1 can be seen.

The highest hardness of 606 HV1 for the multi-track axle was recorded at 4 mm, followed by a decrease in hardness of up to 187 HV1. The lowest hardness of 187 HV1 is found in the overlapping region.

As explained in previous research [32], the decrease in hardness in overlapping layers is an inevitable phenomenon. However, it is noteworthy that even the lowest values of the hardness record exceed the bulk material values, which usually are around 170 HV1.

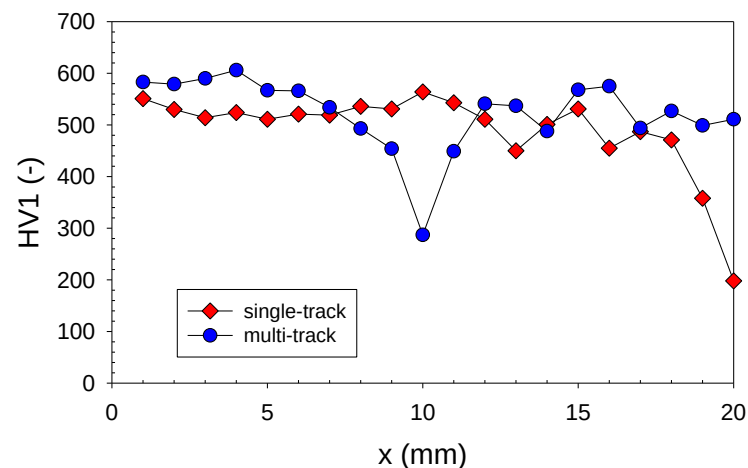


Figure 8. Hardness for single and multi-track model axles, where $x = 0$ mm denotes the inner edge of the axle seat-side of the axle shaft.

3.3. High-Cycle Fatigue Tests (HCF)

All fatigue tests were always performed with an initial bending stress amplitude of 120 MPa in the area under the press fit. At this amplitude, the press-fit area (seat) should reach a durability of 10^7 cycles without failure, which is a requirement of EN13261. If no failure was observed within 10^7 cycles, the amplitude was always increased by 15 MPa, i.e., with bending stress amplitudes of 135 MPa, 150 MPa, and 165 MPa, as shown in Figure 9.

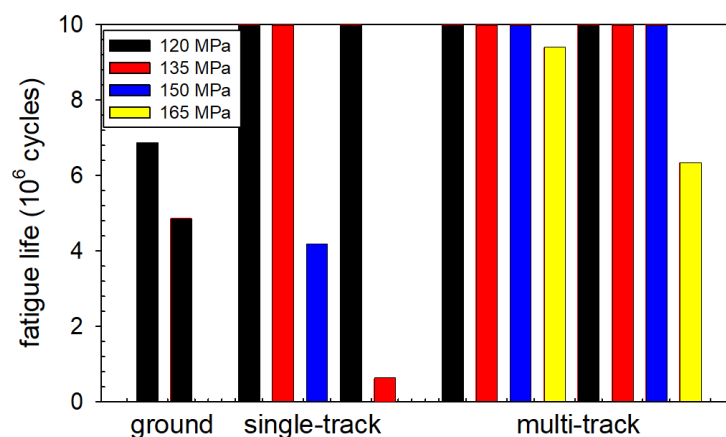


Figure 9. Achieved fatigue life at different stress amplitudes.

The two unhardened (ground) axle models were unable to achieve the minimum required bending stress of 120 MPa. Fractures on these model axles occurred at 4.8×10^6 cycles and 6.8×10^6 cycles, respectively, almost reaching the standard service life.

Model single-track axles consistently reached 10^7 cycles at a minimum bending stress of 120 MPa. Fracture only occurred at elevated bending stress levels of 135 MPa, although in one case it occurred at elevated stress levels of 150 MPa. Compared with the ground specimens, there were increases in both durability and bending resistance.

In both cases, the multi-track model axles withstood 10^7 cycles at 120 MPa, 135 MPa, and 150 MPa. Fractures were only observed at a stress level of 165 MPa after 9.3×10^6 cycles and 6.3×10^6 cycles, respectively.

From the results, it is evident that laser surface hardening is proven to increase the fatigue resistance of axle seats under press-fitting. Although fracture initiation always occurred in the first laser track, i.e., from 4.5 mm to 7.5 mm from the inner edge of the axle seat, the multi-track model axles achieved noticeably higher fatigue resistance.

3.4. Fractography

The representative axle seat of the model after the disassembly and application of magnetic powder inspection is shown in Figure 10. In all cases, the crack appeared only on one of the two model axle seats. As mentioned, the cracks initiated at a distance of 4.5 to 7.5 mm from the inner edge of the axle seat, implying an abnormal drop for the multi-track model axles from the main hardness, as depicted in Figure 8. Initiation occurred mostly from a single initiation spot, but there were short cracks around the initiation spot, which caused chips on the fracture surface. These chips were formed by coalescing of the initiation spot and short secondary cracks, as illustrated in Figure 11. The surface of the seats around the initiation spots was covered with corrosion debris and a number of minuscule cracks (Figure 12a), which is typical of fretting fatigue damage. After the initiation stage, the mechanism transforms from fretting fatigue to fatigue controlled by the range of the stress intensity factor. As indicated in Figure 12b, the fracture in the stable fatigue propagation region is formed by ductile striation patterns, i.e., increments of cracks per cycle.



Figure 10. Representative axle seat after failure.

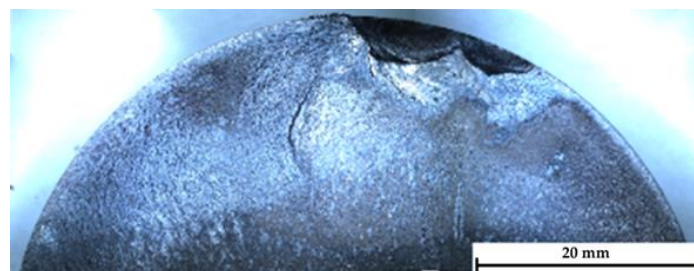


Figure 11. Typical fracture of the axle model.

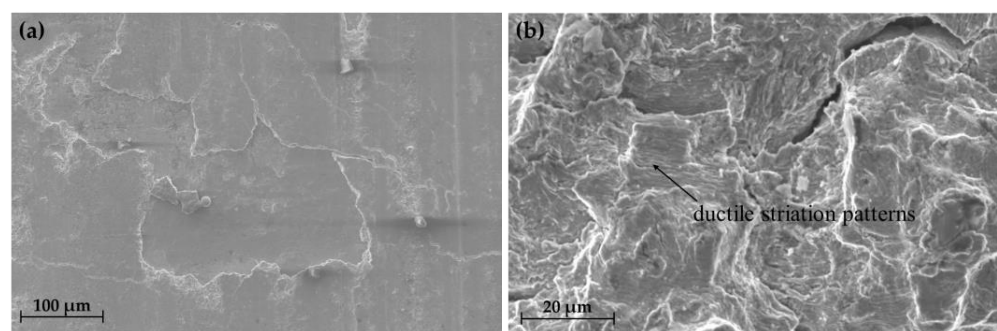


Figure 12. (a) Corrosion debris and a number of tiny microcracks on the seat surface; (b) ductile striation patterns in the fatigue crack growth region.

3.5. X-ray Diffraction

XRD facilitates investigation of the distribution of macroscopic residual stresses (RSs) and microstructural parameters (crystallite size, microstrain, and dislocation density) of thin surface layers ($\sim 1\text{--}10\ \mu\text{m}$) of axle seats before and after high-cycle fatigue tests. From the perspective of RS and microstructural parameters of the laser-hardened surface layers, four basic zones can be distinguished, as elucidated in Figure 1: unhardened (ground), hardened, hardened–unhardened interface, and overlapped (hardened–hardened). Critical zones (so-called microstructural notches) are areas where the values of the investigated parameters show significant changes, i.e., the mentioned interface and the overlapping zones [10]. The critical zone is also considered an area with high undesirable tensile RS values. Therefore, these zones are more susceptible to the occurrence of frictional corrosion, leading to the initiation and propagation of surface cracks.

3.5.1. Before HCF

Figure 13 shows that grinding (i.e., unhardened surface) induced high tensile stresses of 300–500 MPa, which significantly reduced the fatigue life of the sample. On the other hand, compressive stresses (more than $-100\ \text{MPa}$) were detected on the surface of the laser-hardened track. The final state of RS is the superposition of thermal shrinkage and transformation from austenite to martensite/bainite/ferrite. In this case, the transformation effect that caused compressive RS was greater than the thermal effect that generally gives rise to tensile RS.

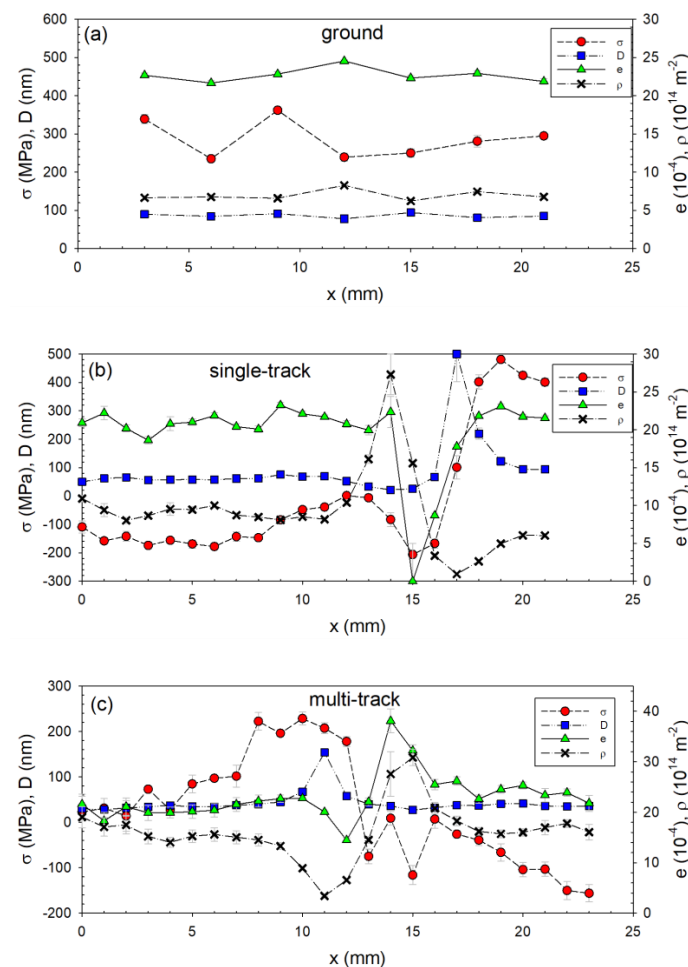


Figure 13. Surface distribution of residual stresses, σ , crystallite size, D , microstrain, e , and dislocation density, ρ , for (a) ground, (b) single-track, and (c) multi-track hardened samples, where $x = 0\ \text{mm}$ denotes the inner edge of the axle seat-side of the axle shaft.

For the single-track sample, Figure 13 shows a microstructural notch (at a distance of approximately $x = 16\text{--}17\text{ mm}$), where there are tensile RSs, high crystallite sizes, minimum microstrains, and minimum dislocation densities. This notch is located at the boundary of the hardened and unhardened (ground) surface (called the partially hardened zone, as shown in Figure 1) and is a potentially a critical zone for surface fatigue crack initialization and propagation.

In the case of a multi-track sample, the distribution of the investigated surface integrity parameters revealed the critical zone at the edge of the overlapping of two tracks, namely, between the track and the subsequent overlapping track (approx. $x = 11\text{ mm}$; called the tempered zone, according to Figure 1). In this zone, similar to the single-track sample, tensile RSs, sharp maximum crystallite sizes, minimum microstrain, and minimum dislocation density were again observed.

According to the Williamson and Smallman method, the small (insignificant) microstrain value and the large crystallite size are indicative of a relatively low dislocation density. Deformation hardening is an important hardening process that involves plastic deformation of the material during forging to significantly increase the dislocation density, i.e., the dislocation density of the ground surface is much lower than on the hardened surface. Therefore, areas of lower dislocation density are usually prone to hardness reduction and are susceptible to frictional corrosion and the initiation of surface fatigue cracks. The lowest hardness is found in the overlapping region, which coincides with the minimum dislocation density, as revealed from a comparison between Figures 8 and 13. High tensile RSs were generated in the surface layers of this microstructural notch; these areas are most likely to initiate surface crack initiation from the XRD point of view.

3.5.2. After HCF

After HCF and after wheel demounting, XRD analyses were again performed on the seats without cracks of each axle model. From the graphs illustrated in Figure 14, it can be seen that after HCF, the compressive RS values did not change within the experimental error; in contrast, the tensile RS transformed into compressive values. This phenomenon can be explained by wheel press-fitting and/or HCF, where the surface layers were plastically deformed; therefore, compressive RSs were generated.

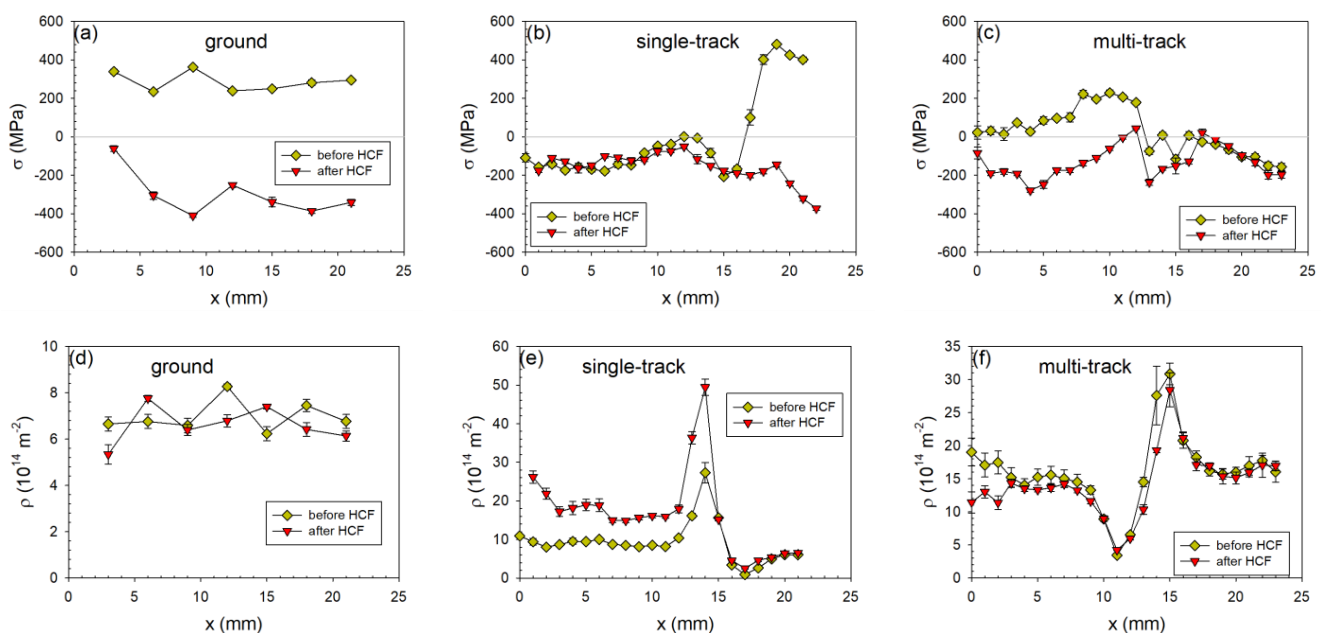


Figure 14. Surface distribution of residual stresses, σ , and dislocation density, ρ , for ground, single-track, and multi-track hardened samples before and after HCF, where $x = 0\text{ mm}$ denotes the inner edge of the axle seat–side of the axle shaft.

The dislocation density was only higher after HCF for a single-track sample, suggesting plastic deformation in the near-surface layers. This trend could be explained by the higher pressing force, where the surface layers are highly plastically deformed. The dislocation density for the other two samples exhibited the same value within the error. Moreover, it is evident from [33] that the creation of microcracks only influences the microdeformation and dislocation density. The final rupture or macrocracks reduces RS, microdeformation, and dislocation density. These phenomena were not observed, so it could be concluded that the samples did not contain any surface cracks; moreover, no cracks occurred on the axle seats examined after the HCF, i.e., 6.8×10^6 with amplitude 120 MPa, 4.2×10^6 with amplitude 150 MPa, and 6.3×10^6 with amplitude 165 MPa for ground, single-track, and multi-track sample, respectively.

The XRD patterns from which the microstructural parameters were calculated are depicted in Figure 15. It is evident that laser hardening caused the formation of oxides (magnetite, hematite, and wuestit) on the surface compared with the ground sample. After press-fitting, HCF, and demounting, there was a reduction in the proportion of oxides for the single-track sample and almost all oxides were removed for the multi-track sample. According to [1], fretting damage starts with the removal of the oxide layer, which is followed by the adhesion of surface asperities in the form of cold-welds, which increases the friction coefficient. The multi-track sample was loaded with a larger number of cycles and to a higher amplitude, which is probably the reason that all oxides were removed.

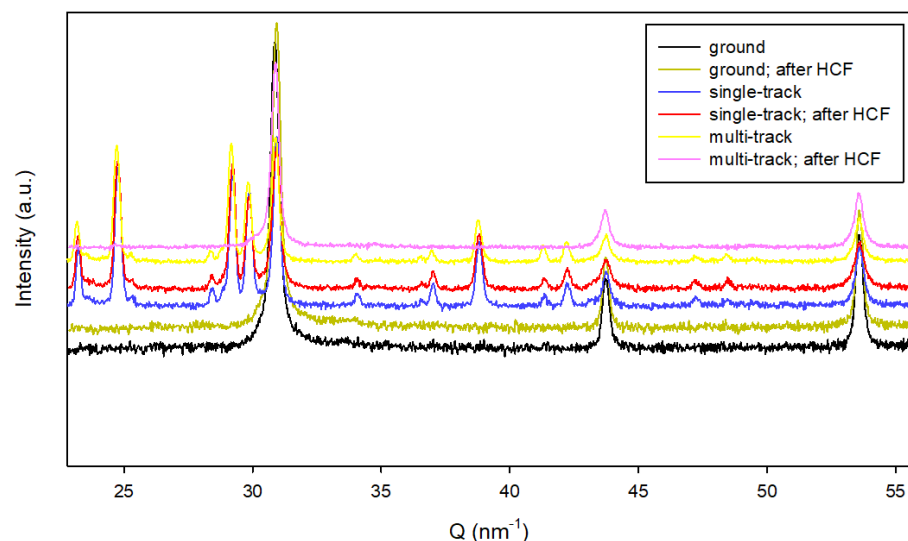


Figure 15. XRD patterns of ground, single-track, and multi-track hardened samples before and after HCF at the distance of 6 mm from the inner edge of the axle seat–side of the axle shaft, where Q is a scattering vector.

Wheel press-fitting and/or HCF itself probably affects the surface of the axle seat. It generates compressive residual stresses and increases the value of dislocation density and hardness; in other words, there is plastic deformation that improves the values of surface integrity parameters that affect the initiation and propagation of fatigue cracks. Based on these results, it can be argued that neither the state of residual stresses before press-fitting nor the density of dislocations determine the fatigue life of railway axle seats.

4. Conclusions

The purpose of this investigation was to explain the relationship of the microstructure, mechanical properties, and surface residual stresses of laser-hardened samples with fatigue resistance. Specifically, three railway axles made of EA1N steel with different surface thermo-mechanical treatments (ground, laser-hardened with and without tracks overlapping) were investigated before and after high-cycle fatigue tests (press fitted, cycled, and

demounted wheels). Various experimental techniques were used for analysis of the surface properties and critical zones of potential surface crack initialization.

A comparison was performed with scaled axle models under conditions corresponding to actual loading mechanisms, where the axle seat was first subjected to frictional corrosion followed by fatigue crack initiation from the crack network.

The key experimentally obtained knowledge can be summarized in the following points:

1. For the unhardened sample, normalized lifetimes at 120 MPa loading were almost achieved. The increase in durability for single-track hardening over the prescribed value was demonstrated to be more than 13%. In the case of hardening with continuous seat coverage, it was more than 25%.
2. Both the compressive and tensile residual stresses were present on the hardened track surface in the axial direction before press-fitting.
3. The critical zones accompanied with decreases in hardness, tensile RS, and steep changes in microstructural parameters values were identified.
4. High-cycle fatigue tests showed that the press-fitting caused maximum load initialization in the hardened area under the flange.
5. Typical fretting fatigue damage occurred on the surface of the tested samples. A final rupture appeared in this area.
6. The microstructure notches (steep change in XRD parameters) could be reduced to a certain extent by changing the hardening parameters; nevertheless, it was impossible to remove them. Inappropriate placement of the laser track in a critical zone of the axle could ultimately lead to premature fracture. Therefore, the crucial step is the proper position of these notches on the axle seats, to ensure that they were not in the main loaded part of the seat. All fatigue cracks after the final rupture were initialized out of the critical zone; thus, the position of the laser tracks was appropriate from the critical zone position point of view.
7. It seems that neither the state of residual stresses nor the dislocation density before press-fitting determines the fatigue life of a railway. The influence of residual stresses and dislocation density influence on fatigue life was reduced by axle press-fitting seats.
8. Based on this study, the determining parameter of service life is the development of fretting corrosion, which is consistent with theoretical knowledge. The axle with the highest hardness had the highest fatigue life.
9. Further research is needed to distinguish the effect of press-fitting and cyclic fatigue on the residual stresses and microstructural parameters.

Laser hardening has been shown to increase the fatigue life of model railway axles. Laser-hardened tracks resist not only the frictional corrosion mechanism, but also the actual damage after pressing. In addition to increased durability, there is the potential for reuse of axles after demounting, without the need to re-profile the axle seat.

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