Influence of Overlapping on Surface Integrity Parameters of Laser-hardened Railway Axles

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Abstract: The paper describes the influence of overlapping of tracks on the state of residual stresses and microstructural parameters of laser hardened railway axles made of EA1N steel. It has been found that the tensile residual stresses, large crystallite size and low microdeformation are located on the surface of overlapping tracks. This zone, accompanied by a decrease in hardness, can be a potential area for crack initialization.

Keywords: railway axles; laser hardening; X-ray diffraction; microstructure; hardness.

1 Introduction

This research is focused on the development of surface treatment technology of railway axle seats using laser hardening to increase resistance to fatigue failure. Railway non-powered axles made of standard EA1N steel were examined.

For single-track laser hardening, the compressive residual stresses (RS) were found out on the surface of the hardened area, inside the laser track. On the other hand, the bulk material (machined surface) could reach high tensile RS, see [1]. This zone with a significant change in RS is usually an area of potential surface crack initialization.

Using multi-track laser hardening with overlapping, the part of the hardened zone is re-hardened. Therefore, the different zones are generated in and near the overlapped zone, see Fig. 1. The re-hardened and tempered zones are usually accompanied by a decrease in hardness [2, 3]. With the presence of other undesirable values of surface integrity, especially tensile residual stresses and microstructural notches, these zones are typical areas of initialization of surface cracks [1].

Therefore, it is important to achieve optimal characteristics of surface integrity of the axle at critical zones, including fatigue resistance, which is positively affected by compressive RS [4].

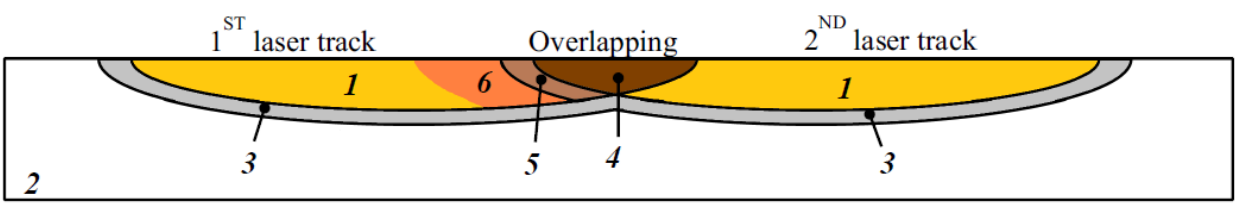

Fig. 1: Zones generated by multi-tracks laser hardening with overlapping: (1) hardened, (2) base material, (3) partially hardened, (4) re-hardened, (5) tempered partial re-hardened, and (6) tempered zones [2].

2 Experimental details

For experimental tests, a forged turned semi-finished product made of EA1N steel was used. The hardening was carried out circumferentially, following the hardening method, on axle seats with a controlled hardening temperature of 1150 °C, and a beam speed of 3 mm/s performed by the *Laserline LDM3000-60* in the company RAPTECH s.r.o. The width of the overlapping of tracks was 5 mm.

Metallographic specimens were hot embedded into conductive bakelite resin with the carbon filler and prepared by machine grinding and polishing. Structure was revealed by etching in 4% Nital (98 ml ethanol + 2 ml HNO_3). Microstructure was investigated by the optical microscope *Zeiss Axio Observer Z1M*.

Macroscopic residual stresses (RS) were determined using the *X'Pert Pro MPD* diffractometer by X-ray diffraction (XRD) and chromium radiation. The RS were analysed across the overlapped hardened tracks, see Figs. 2 and 3. The values of RS were calculated from lattice deformations determined based on experimental dependencies of $2\theta(\sin^2\psi)$ assuming a uniaxial state of residual stress, where θ is the diffraction angle, ψ the angle between the sample surface and the diffracting lattice planes. The diffraction angle was determined as the center of gravity of the Cr$K\alpha_1\alpha_2$ doublet diffracted by the lattice planes $\{211\}$ of the α-Fe phase. The X-ray elastic constants $s_1 = -1.25$ TPa^{-1}, $1/2s_2 = 5.76$ TPa^{-1} were used for the stress calculation. The crystallite size (size of coherently diffracting domains) and microdeformation (inhomogeneous distribution of elasto-plastic deformation on a microscale; a grain size) were determined from the XRD patterns obtained using the cobalt radiation and the Rietveld refinement, performed in *MStruct* software. The irradiated volume was defined by experiment geometry, the effective penetration depth of the X-ray radiation (approx. 5 and 10 μm for chromium and cobalt radiation, respectively), and the pinhole size (4×0.5 mm^2).

Hardness was evaluated as Vickers hardness HV10 using the *Vickers Limited HTM*.

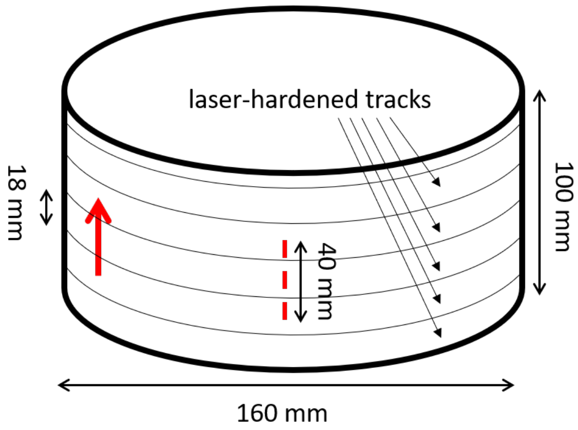

Fig. 2: Diagram of analysed sample, where arrow denotes the XRD measurement direction and dashed analysed line.

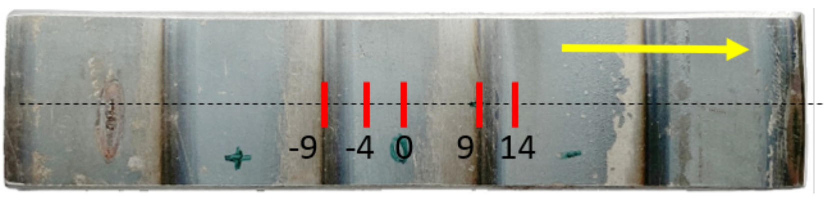

Fig. 3: Photo of multi-track hardening, the arrow represents the direction of overlapping tracks.

3 Results and discussions

Hardened depth evaluated from macrostructure was 1.5–2 mm, which is typical for laser hardening. The microstructure of the hardened tracks and the boundary between the tracks and base material was homogeneous in all cases. Microstructure of the hardened tracks corresponded to very fine-grained tempered martensite, in the direction of base material being continuously changed to the mixed martensitic and ferritic-pearlitic structure.

The microstructure of the base material was purely ferritic-pearlitic and corresponded to EA1N steel standard. Microstructure changes in the direction from hardened track to base material are documented in Fig. 4.

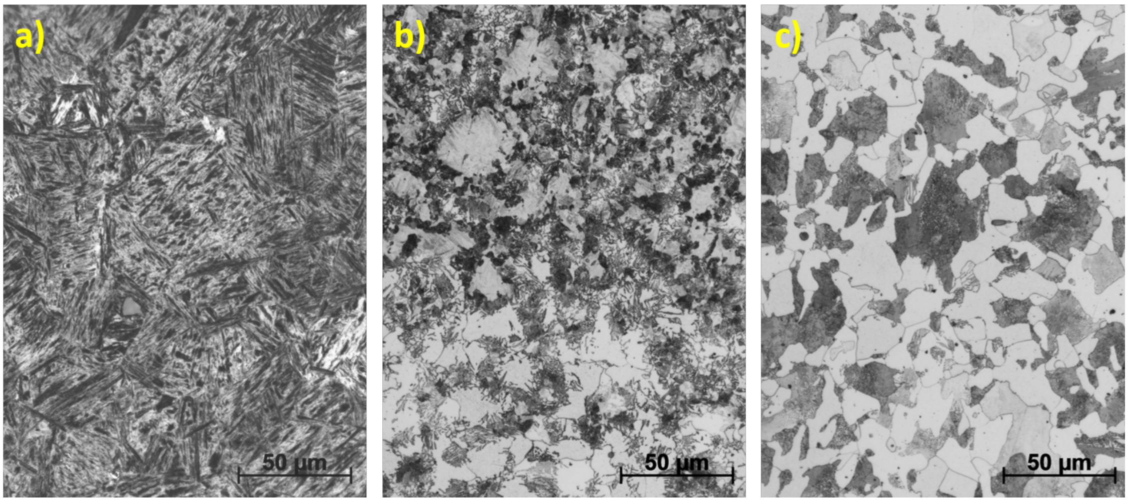

Fig. 4: a) Martensitic microstructure of the hardened track, b) mixed microstructure of partially hardened zone, and c) ferritic-pearlitic microstructure of base material.

Nevertheless, particular attention was paid to the overlapping of the laser tracks, as it is a zone where local deviations from both microstructure and hardness usually occur. Hardness analyses were performed across the overlapping and hardened zones, see Fig. 5, where the inhomogeneous course was found. This evolution confirmed the expectation of hardness decreasing in the tempered and re-hardened zones. Therefore, the hardness reduction in the overlapping zone is, generally, necessary to expect. What is, however, important is that in spite of some hardness decrease resulting from a partial tempering of the previously hardened material, the drop is not absolute in terms of the actual hardness value, which remains considerably higher than the hardness of the base material, which is approx. 170 HV.

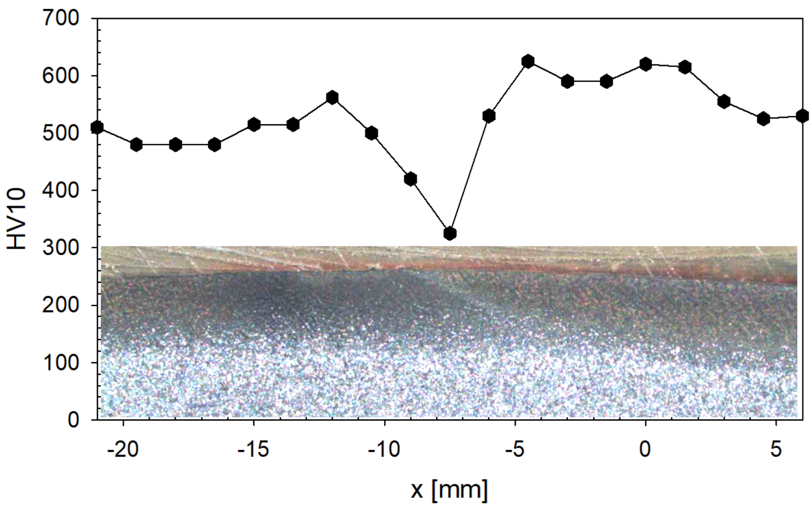

Fig. 5: Course of HV10 hardness in surroundings of laser tracks overlapping.

Detailed analyses of the surface macroscopic RS, microdeformation, and crystallite size of the laser-hardened sample with overlapped tracks are depicted in Fig. 6. The figure shows three overlapped tracks, hardened from left to right.

Stresses formed on the hardened surface because of rapid thermal heating and consequent cooling associated with phase transformation. Therefore, stresses occurred as a result of the superposition of thermal (tensile effect) and transformation (compressive effect) stresses and generally could reach high values.

Same as for single-track hardening [1], the compressive RS were found on the surface of the hardened track due to the dominant transformation effect. In the case of tracks' overlapping, the transition zones with different values of investigated parameters were observed. Fig. 6 shows the unfavourable surface tensile RS, large crystallite size, and low microdeformation localize at the boundary of the track (at a distance of 9 mm from the x-axis origin). At this distance (at the left boundary of the track), the temperature was not so high to phase transformation only the original microstructure was tempered. Therefore, the crystallite size was larger than in the track and heat-affected zone. The tensile character of RS was very likely caused by stress revealing from elevated temperature and subsequent cooling at this zone. For the same reason, a local minimum of microdeformation probably appeared. The lowest microdeformation were placed at the boundary of the track, where the thermal effect was dominant and, therefore, the grain distortion was reduced.

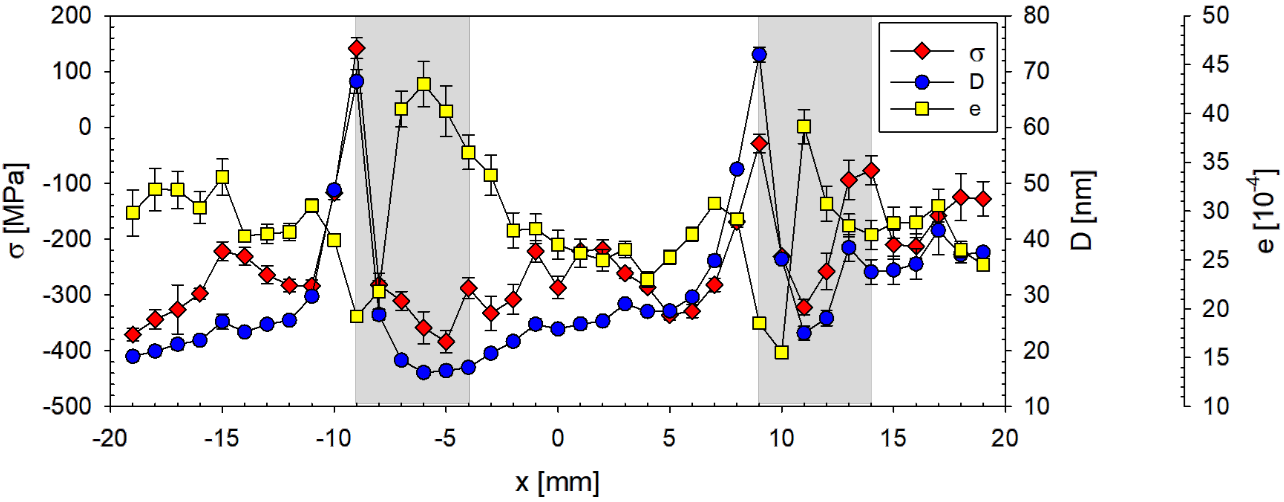

Fig. 6: Distribution of surface macroscopic residual stresses σ, crystallite size D, and microdeformation e across the hardened tracks in the direction perpendicular to the hardening. Grey areas denote the overlapping of tracks.

4 Conclusions

The overlapping (re-hardened) and surroundings tempered zones are accompanied by a decrease in hardness, microstructure changes and by extremes in values of RS, crystallite size and microdeformation, see Figs. 5 and 6. The distributions of investigated surface integrity parameters are in very good agreement with high-cycle fatigue damage, when the initiation of fatigue cracks occurred exactly at the boundary between two laser tracks, namely preceding track and subsequent — overlapping track.

Acknowledgement

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