Influence of Laser Hardening and Resulting Microstructure on Fatigue Properties of Carbon Steels

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Cylindrical specimens of a CSN 12050 carbon steel, equivalent to the UNS G 10420 steel, with two different initial microstructures, normalized and heat treated, were surface processed without melting by a 2.5 kW, CO_2 laser to study the effects of laser-beam hardening and resulting microstructure on fatigue properties and mechanisms. Two configurations of circumferential laser passes were made, resulting in one and three separate surface hardened lines, respectively. Fatigue resistance was studied using alternating bend tests. A detailed metallographic study and x-ray measurements of surface stresses were carried out. It was shown that the laser beam hardening under different conditions either reduced or slightly improved the fatigue life.

Keywords carbon steels, fatigue life, laser hardening

1. Introduction

In recent years, technologies of laser treatment of metallic materials have been widely developed due to the extensive use of inexpensive powerful lasers. Besides laser cutting and welding, laser hardening is one of the most powerful technological processes. Laser hardening permits conduction of surface heat treatments in cases where classical hardening methods are not applicable, for example, local hardening in notches with high-stress concentrations. One of the greatest advantages of laser processing in such cases is the possibility to localize exactly the time and space heating of a material surface, which results in a surface-treated zone with a sharp structural interface.

A considerable amount of literature about laser processing has already been published. The first group deals with effects of various parameters of laser processing on properties of laser-treated material, such as microstucture, hardness, and shape of the surface laser-hardened zone. Several thermomechanical models of heating and subsequent cooling processes have been successfully introduced to explain the characteristic properties of the treated material. References 1 to 6 describe connections between chemical composition of carbon steels and parameters of laser processing with properties of treated zones. The main conclusion of these works is that surface microhardness can be increased more than three times if an optimum combination of chemical composition and laser parameters is used. Such a large increase in the surface hardness is particularly important for increasing the wear or corrosion resistance (Ref 7) and the contact fatigue life (Ref 8).

Results of other types of fatigue loading are ambiguous. For instance, in Ref 9 the fatigue properties of a laser-hardened carbon steel equivalent to the UNS G 10420 steel with axial and spiral surface laser lines were studied on specimens with a circular cross section and small diameter (7 mm), subjected to cyclic plane bending. Different fatigue properties of laser-treated zones and zones between laser lines with untreated material were demonstrated by two different positions of specimens: lines placed in the region of the maximum bending stress and the untreated zone between the two neighboring lines in this region, respectively. In comparison with original untreated specimens, the fatigue strength of laser-treated zones was >60% higher . On the contrary, the fatigue strength of the surface between two lines was significantly lower. These results are in a good agreement with Ref 10, where the theory of damage mechanics was applied to establish optimum parameters of the laser treatment. In Ref 10, cylindrical specimens made from the UNS G 10420 steel with a laser-treated type-V, ring-shaped notch were tested under tensile alternate load. The fatigue limit after the laser treatment increased more than 2.5 times. Reference 11 documents an influence of different configurations of surface laser lines on the fatigue properties of specimens of 150 by 17 by 11.5 mm made from a 50CrV4 steel under three-point bending. If a single axial laser-hardening line was made using a 5 kW output square beam 15 by 15 mm, fatigue limit was ~40% higher. This favorable effect was almost completely eliminated by additional laser treatment in the transversal direction.

In general, for materials and components under fatigue loading, the influence of large values of the surface hardness on fatigue properties is known to be positive. However, the sharp structural interface, often connected with significant local residual stresses, can have a detrimental effect on the fatigue life. Such an interface, also called structural notch, is an initiation site for fatigue cracks. This is one of the reasons for different results of fatigue tests of laser-processed materials and for possible deterioration of fatigue resistance by laser processing in some cases. Reference 12 describes these negative effects of the laser heat treatment of various engineering materials on fatigue properties. The reduction of the fatigue strength depends on the material composition and laser parameters. It is evident that laser surface treatment of steels can significantly improve fatigue properties, in addition to wear and corrosion resistance. The goal of this work was to verify and explain the influence of

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laser hardening of carbon steels with two different structures with a separate laser-treated line and three lines with an interaction.

2. Experiments

A CSN 12050 carbon steel, equivalent to UNS G 10420 steel, in two basic heat treatment conditions—normalized and heat treated—was used as an experimental material. Fatigue tests were carried out using smooth, cylindrical specimens without notches (Fig. 1), polished before the laser treatment. At the final steps of polishing, the sequence of abrasive papers of 280, 400, and 600 grit were used. These values of grit correspond to the abrasive diameter of 60, 50, and 40 μm, respectively. The hardness of the normalized material was 206 HB, the corresponding ultimate tensile strength (UTS) was 720 MPa, and the hardness of the heat treated material, 266 HB, corresponded to UTS = 905 MPa. The specimens were laser treated on the continual CO_2 laser with a maximum power of 2.5 kW. Two configurations of circumferential laser lines were made—a single line in the center of the specimen or three separate surface hardened lines in the gauge section (Fig. 1), respectively. In the case of three passes, the distance between edges of the lines was ~3 mm. The laser beam was a circular cross section resulting in surface lines ~2.8 mm wide. The laser parameters—the power of the beam 0.7 kW and the scanning speed 1.2 m/min—were used as operating parameters. Before the laser processing, the specimen surface was covered with a black antireflective varnish to allow an optimum absorption of the laser beam energy with the minimum reflection. The effect of one separate line and of an interaction of three lines according to Fig. 1 was studied on both the basic materials. Two methods of removal of the antireflective layers after the laser treatment were used: (a) wiping the varnish off with textiles and acetone or (b) repolishing with a removal of 0.01 to 0.02 mm material from the surface with an abrasive cloth and papers. The same sequence of grit previously mentioned was used in the final step. Table 1 gives a survey of specimen groups.

Table 1 Groups of specimens and their treatment

Basic material	No. of lines	Repolishing
UNS G 10420 normalized	0	Yes
	0	No
	1	Yes
	1	No
	3	Yes
	3	No
UNS G 10420 heat treated	0	No
	1	Yes
	1	No
	3	No

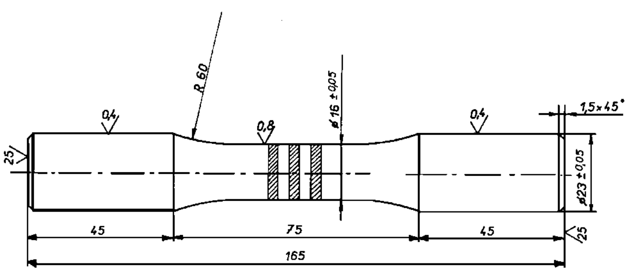


Fig. 1 Fatigue specimen with three circumferential laser treated lines. Dimensions are in mm; √ indicates surface finishing

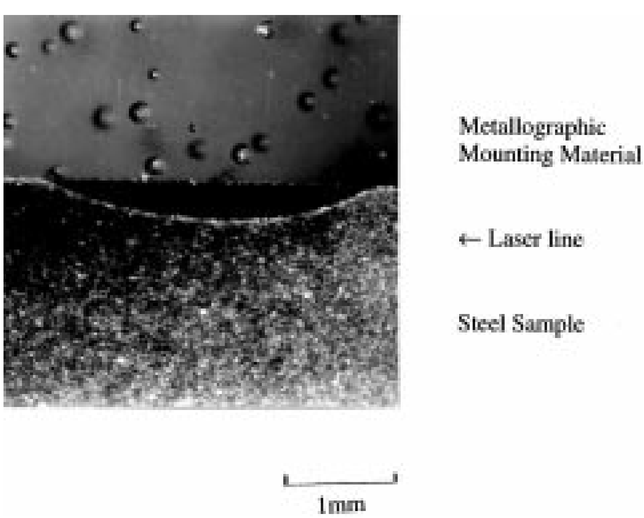


Fig. 2 Axial cut of the specimen showing cross section of the laser line, heat treated bulk material, and specimen surface

All specimens were examined by fluorescent magnetic particle inspection before fatigue tests. Metallographic analysis and surface examination in the region of laser-treated zones by scanning electron microscope were carried out. No surface microcracks were found on any specimen. The maximum depth of laser-treated zones was 0.35, ±0.05 mm (Fig. 2). The sharp interface between the laser-treated material and bulk material connected with the sudden changes of the subsurface microhardness (Fig. 3) is very typical for laser-treated materials. A large increase in hardness values was reached: 3.2 times for the heat-treated steel and 3.8 times for the normalized steel.

The martensitic microstructure in the laser-treated zones of specimens with the heat-treated basic structure was very fine

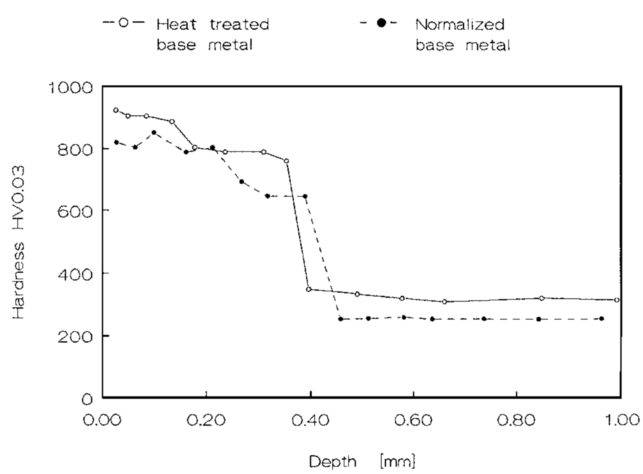


Fig. 3 Hardness as a function of distance from the sample surface through the laser-affected zone

and homogeneous. However, the laser-treated zones of normalized specimens contained mostly a duplex microstructure composed from zones of not fully dissolved pearlite and oversaturated ferrite (Fig. 4). Typical martensitic needles were observed only in the very near surface layer in the center of the treated zones (Fig. 5). This is discussed later.

Before fatigue testing, x-ray measurements of residual stresses were carried out on several specimens. The diffraction method of the reflected perpendicular chromium-$K\alpha$ ray with silver as a reference material and with a rotation of the specimen was used. Some attempts to measure residual stresses were also carried out on the surface of the laser-treated zones. However, the untempered martensite resulted in a great diffusion of diffraction lines so that the center and shift could not be evaluated. Therefore, only regions outside of the laser lines could be measured: two or more surface points on specimens with the single line and points between and outside of the lines on specimens with three lines.

Fatigue tests were conducted under alternating bend loading ($R = -1$) with a constant value of bending moment for the entire gauge length. The test frequency was 50 Hz. All tests were carried out to rupture. The fatigue limit was verified on the basis of at least 10 million cycles.

3. Results and Discussion

Figure 6 shows results of the fatigue tests for normalized material, and Fig. 7 shows results for heat-treated basic material. It is evident that the most important factor affecting the fatigue properties is repolishing after laser processing. The fatigue life of the unrepolished laser-treated specimens is

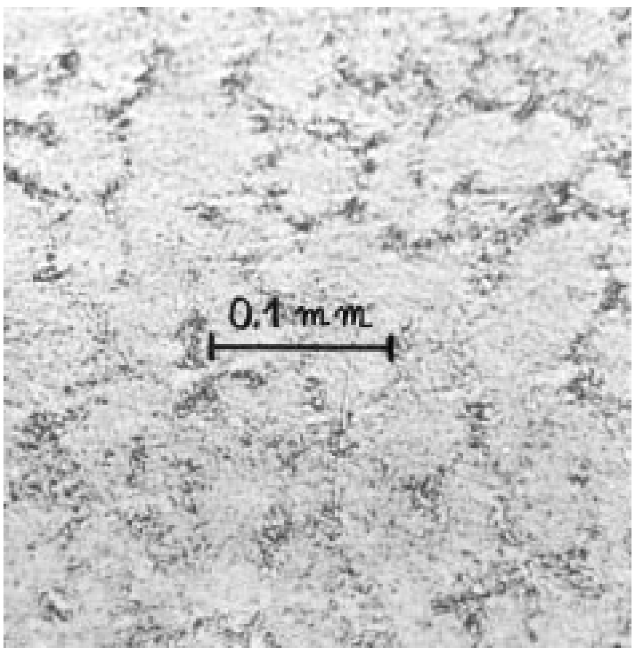


Fig. 4 Partially dissolved pearlite in laser-treated zones on normalized bulk material. 200×. (Art has been reduced to 95% of its original size for printing.)

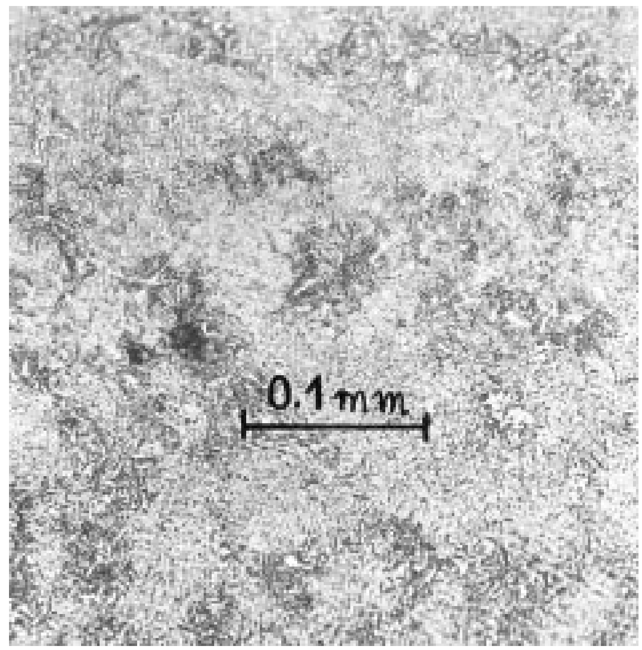


Fig. 5 Needles of martensite in the very near-surface laser treated layer on normalized bulk material. 200×. (Art has been reduced to 77% of its original size for printing.)

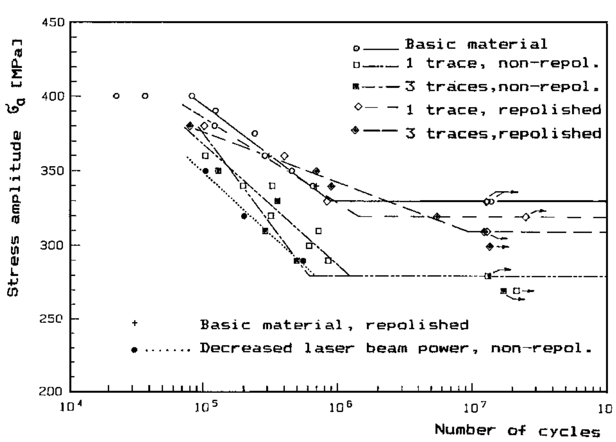


Fig. 6 Fatigue life of all groups of normalized specimens

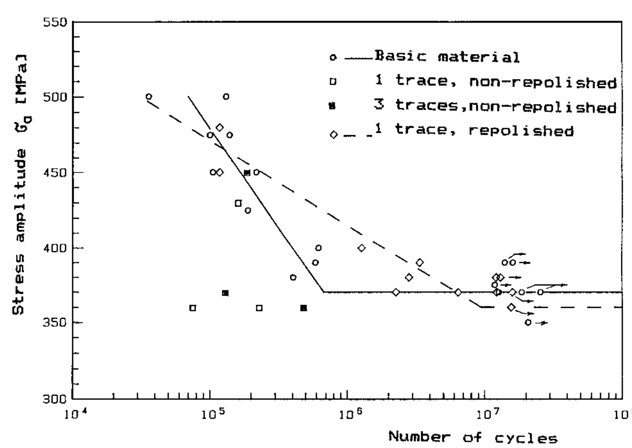


Fig. 7 Fatigue life of all groups of heat-treated specimens

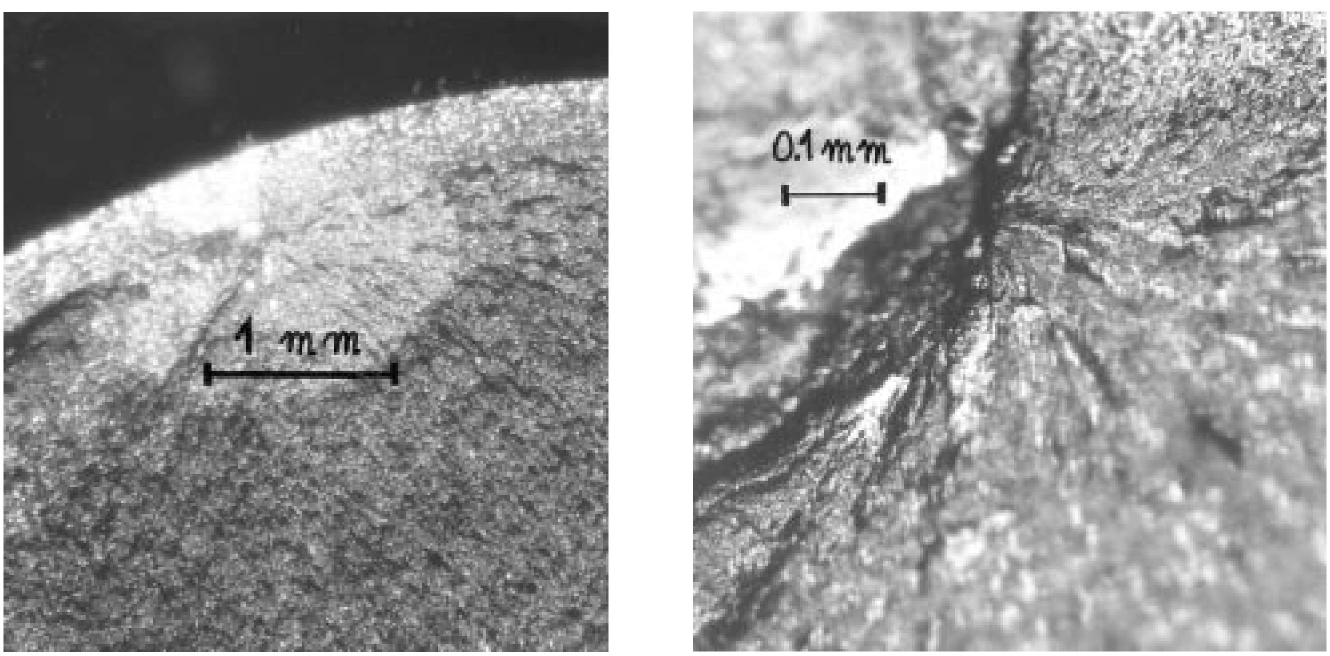
significantly lower in comparison with the specimens, not laser treated, in both cases of bulk materials and both configurations of the runs. The differences are particularly distinct at the lower region of loading amplitudes, near the fatigue limit. In the case of the heat-treated basic material, the fatigue life of the laser-treated unrepolished specimens is very short, ~10^5 cycles even for the loading amplitude ±360 MPa, which corresponds to the fatigue limit of the basic material. Fatigue curves of these specimens are very steep, almost vertical, which is typical for high-strength steels with sharp notches. The fatigue limit of the normalized material after the laser processing is ~16% lower in comparison with the material not laser treated. The fatigue properties of the unrepolished specimens are practically independent of the number of laser runs.

Significantly different results were obtained for the specimens repolished by abrasive papers using 280, 400, and 600 grit at the final step. The fatigue limit was only 5 to 7% lower (no more than 20 MPa) in comparison with the untreated material in all cases. In the region of higher loading amplitudes exceeding the fatigue limit, the fatigue life of the laser-treated specimens was slightly higher.

Significant differences between repolished and unrepolished specimens exist at crack initiation sites. Cracks initiated on the surface boundary lines either between the basic material and the treated zones or on the surface in the region of the zones on unrepolished specimens, without any exception. In the case of repolished specimens, no connection between initiation sites and the treated zones on the normalized specimens and on most of the heat treated specimens was found. Cracks initiated at >3 mm outside the single or triple lines and never initiated between the three lines. This indicates that the fatigue resistance of the region of laser-treated zones, including gaps between lines, was better in comparison with the untreated material. Otherwise, at least in some cases, cracking should also occur in the central region of specimens. Further experiments with the entire treated gauge section of specimens—with four additional laser passes—could confirm and quantitatively determine the improvement of the fatigue resistance. A subsurface crack started under the laser-treated zone in the structural interface on several repolished laser processed specimens with the heat treated basic material. Figure 8 documents one of the cases of the subsurface fatigue crack growth corresponding to the light semielliptical area. The detail (Fig. 8a) shows that the crack initiation occurred on a defect, probably inclusion, located at the interface between the treated and basic material. Although the defect is small, the interaction with the stress concentration was sufficient for the crack initiation. The subsurface crack initiation was always connected with the high number of cycles, up to 7 million. The subsurface mechanism is also well known in material classically heat treated, for example, surface quenched, carburized, and nitrided (Ref 13).

Two additional fatigue tests of normalized specimens treated with the decreased power of the laser beam, 0.5 kW, and not laser treated, but repolished specimens, were carried out to verify whether the harmful effect of the treatment without repolishing was caused by a surface micromelting and if the beneficial effect of the repolishing was caused by induced residual pressure stresses in comparison with the untreated unrepolished specimens. Figure 6 shows these results. No favorable influence of repolishing untreated specimens and power reduction is evident. Figure 9 shows the results of the x-ray stress measurements. The negative residual stresses in the gaps between the treated lines in the case of three laser passes can explain the fact that cracks did not initiate in these gaps but outside the central laser treated region and outside the lines and gaps.

A detailed metallographic analysis of subsurface laser-treated layers, aimed at explaining the influence of the factor of



(a) (b)

Fig. 8 Example of subsurface crack initiation under the laser-treated zone on heat-treated bulk material. (a) Macroscopic view. (b) Detail repolishing, was carried out. A measurement of specimens' diameters before and after repolishing showed a decrease up to 0.04 mm in diameter corresponding to the 0.02 mm surface layer polished off. Taking account of Fig. 5 and 6, it is evident that on specimens of normalized material, an essential amount of the very near surface layer containing martensitic microstructure and the almost dissolved pearlite was polished off (layer 1 in Fig. 10). The removal of the martensitic surface layer likely caused a redistribution of surface and subsurface residual stresses resulting in the change of the initiation sites of the cracks. Untempered martensite is namely an oversaturated structure having a higher volume in comparison with more equilibrium tempered structures or pearlite. This hypothesis should continue to be studied and verified by alternative methods of residual stress measurement.

The microstructure of the laser-treated zones on specimens with the heat-treated bulk material was very different from that of normalized specimens; it was fine, homogeneous untempered martensite. Therefore, in this microstructure, no differences on the surface and subsurface regions could be observed. However, a measurement of the surface and subsurface microhardness demonstrated that the central very near-surface layer of the laser-treated lines on unrepolished specimens (layer 1 in Fig. 10) had higher values of hardness in comparison with central parts of these zones (Fig. 11a). It indicates surface martensite to be significantly more oversaturated in comparison with the subsurface martensite. Consequently, the redistribution of surface residual stresses due to repolishing was probably similar to the normalized laser treated specimens. Looking at Fig. 11, where the values of subsurface microhardness for the laser-treated zone on a normalized specimen are shown, and comparing the differences of the hardness with those for heat-treated specimens (Fig. 11a), it can be concluded that differences of residual stresses on specimens with the heat-treated bulk material before and after repolishing, respectively, are probably greater in comparison with the normalized specimens. This could explain why unrepolished laser-treated specimens with the heat-treated bulk structure had poor fatigue resistance and why the fatigue properties were significantly improved by repolishing.

The differences of the surface and subsurface structures of the laser-treated zones can be explained by different heating and subsequent cooling velocities. After the incidence of

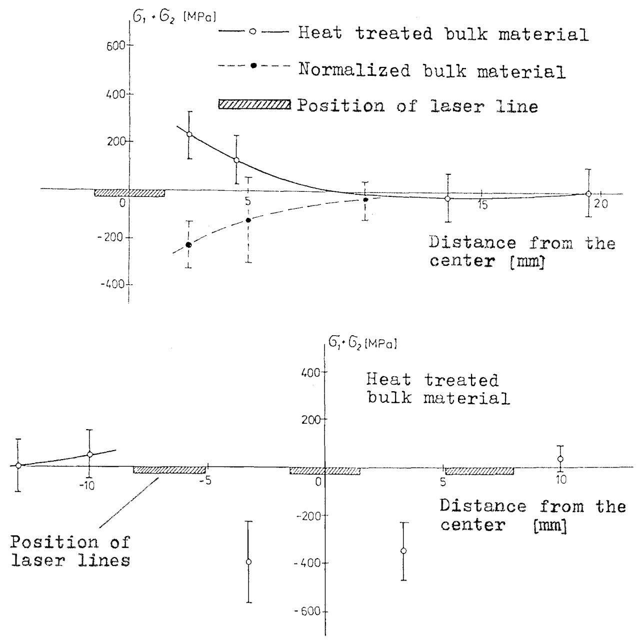


Fig. 9 Residual stresses $\sigma_1 + \sigma_2$ outside laser-treated lines as a function of axial distance from the specimen center along the surface. (a) Specimens with a single line. (b) Specimens with three lines

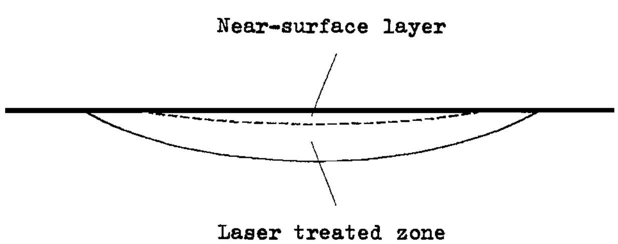
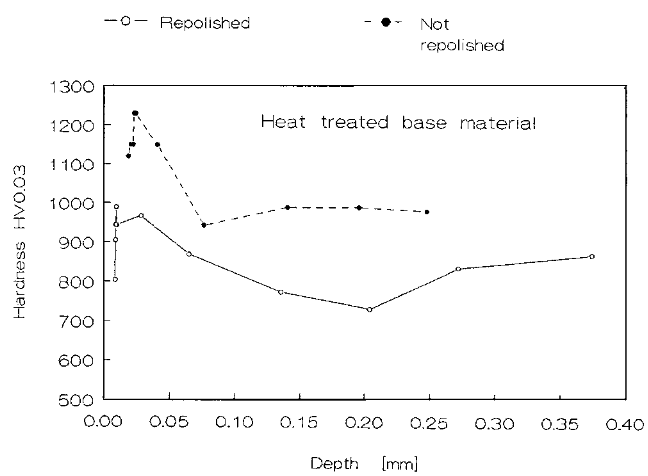
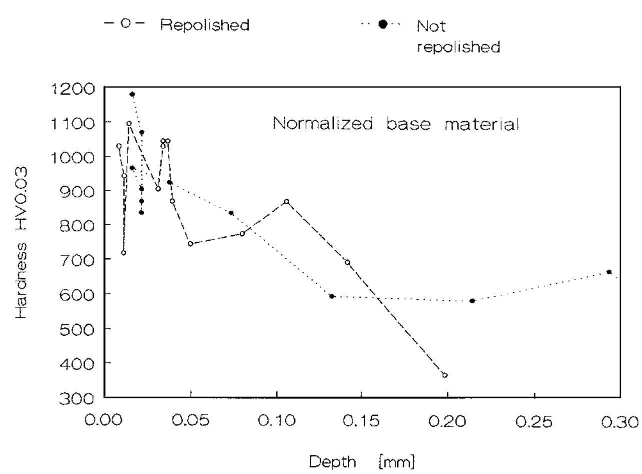


Fig. 10 Schematic view of layers inside laser-treated zones



(a)



(b)

Fig. 11 Subsurface microhardness inside laser-treated zone on specimen with (a) heat treated and (b) normalized bulk material a laser beam onto a surface, the very near-surface zone of the laser-treated line (Fig. 10) is heated first, which results in the most perfect diffusion and solution of carbon in ferrite. This is particularly evident in the case of normalized material where carbon is concentrated in pearlitic grains and the diffusion must occur within greater distances than in already heat-treated structures. As the subsurface zone is heated later and is being cooled by surrounding bulk material, the time of the arrest on the temperature of austenite is not likely to be adequate to enable the complete solution of pearlite (Fig. 4). Consequently, differences of microstructure and properties within laser-treated zones seem to be a possible character of laser technology. Therefore, a high sensitivity of materials heat treated by laser beam on further surface finishing should be expected.

4. Conclusions

An influence of laser hardening on the fatigue life of a medium carbon steel CSN 12050, equivalent to a UNS G 10420 steel, with two different basic microstructures was studied on the cylindrical specimens with one and three circumferential laser beam lines to find mechanisms of fatigue damage after different laser treatment. The main results of alternating bend fatigue tests and subsequent metallographic analysis, x-ray measurement of residual stresses, and other analyses can be summarized as follows:

- Fatigue properties of the laser-hardened material were significantly influenced by the finishing operation—repolishing after laser processing. The fatigue limit of the repolished material was only slightly reduced in comparison with specimens not laser treated in both basic materials, normalized or heat treated. The fatigue life in the region of higher amplitudes was either not affected or was slightly increased.
- Both fatigue life and fatigue limit were significantly lower in comparison with the basic materials for unrepolished specimens after the laser treatment. Cracks initiated on the surface in the center of the lines or in the boundary lines between the laser-treated zones and the basic materials.
- No differences between specimens with three circumferential laser lines and with a single run were observed.

The results show that there are assumptions for successful application of laser hardening of carbon steels for an improvement of fatigue properties in special cases, particularly if local heat treatment is requested, for example, in notches. The final results are, however, very sensitive to the parameters of the process, initial composition, and microstructure of materials and other factors, such as finishing operations.

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