Producing compressive stresses in the surface layer of spheroidal graphite cast iron by laser hardening

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Abstract. The purpose of the examined laser beam induced surface modification technology was to produce compressive stresses in the surface layer of the workpiece. The presence of residual compressive stresses increases the fatigue limit. The compressive stresses generated by investigated laser surface treatment were compared to shot peening technology results, and has been found to be equivalent.

1. Introduction
Compressive stress works contrary to the forces that occur during fatigue loading, thus increasing the fatigue limit. During shot peening the crystal lattice is distorted, and the lattice constant decreases due to the impact of the particles, thus creating residual compressive stresses in a material. The goal was the same during laser hardening, but on a different principle. The advantage of laser beam technology is that it is precisely controllable, more localized than shot peening, and can also handle hard to reach areas [1-5].

Transformations during laser hardening are the followings: At room temperature in cast iron body-centered cubic lattice structured ferrite presents, which heated above \(A_{C3}\) transforms to face-centered cubic lattice structured austenite. Ferrite can only dissolve a few carbon atoms, and austenite can the most, compared to other forms of iron. Above \(A_{C3}\), carbon diffuses from graphite into austenite. With a sufficiently high cooling rate and carbon content, austenite will not transform back to ferrite, but martensite. Martensite (body-centered tetragonal) lattice is a distorted version of ferrite lattice, because it has an interstitial carbon atom in the structure. High cooling rate is needed to prevent the diffusion of carbon. So martensite has a lattice structure that is supersaturated with carbon, and has larger unit cell than both the ferrite and the austenite. (see Figure 1).

This is how the compression stress is created, but also the direction of the heat transport plays an important role in generating residual stress: During bulk hardening, the workpiece is cooled from the case to the core by the applied cooling medium, so that the martensitic transformation (i.e., the compressive stress of its formation) resulting in a higher specific volume also occurs from the case to the core.
As a result, tensile stress is created near the surface and compression stress is developed far from the surface, in the core of the workpiece. This process is reverse and the results are the opposite when performing laser hardening: because the whole piece does not heat over the AC3, only the surface layer, so the workpiece itself functions as a cooling medium, with significant efficiency. Therefore, residual compressive stresses can be produced in the surface by laser beam hardening but cannot be done by bulk hardening [6-8].

2. Experimental investigations

2.1. Test material
The investigated material was GGG50 (material no. 0.7050) according to DIN EN 1563, a ferritic-pearlitic spheroidal cast iron. The chemical composition is shown in Table 1. The metallographic image of the base material is shown on Figure 2.

The base material consists of three microstructural elements: ferrite (white), pearlite (light brown) and graphite (black). The graphite morphology is spheroidal and has an average diameter of 30 µm.
Table 1. Chemical composition of our test substances compared to the standard

|                  | Chemical components (wt%) |
|------------------|---------------------------|
|                  | C   | Si | Mn % | Cu % | Mg % |
| Test substances  | 3.55| 2.4| 0.28 | 0.48 | 0.041|
| DIN EN 1563      | 3.5 – 3.7 | 2.2 – 2.8 | max. 0.4 | 0.4 – 0.6 | 0.035 – 0.055 |

2.2. Laser equipment and parameters
A Trumpf TLC 105 high-frequency CO₂ laser device with maximum 5 kW output power was used for the experiments. The laser beam was deflected by a 5 axis CNC machine tool. One-axis scanning head with a vibrating mirror was used for laser hardening.

![Figure 3. Sketch of the vibrating mirror and the line focus design](image)

The vibrating mirror causes virtual line focus on the surface. Harmonic oscillation was used at 100 Hz frequency with an angular deviation of ± 4°. (as the sketch shows in Figure 3). This scan head is able to produce a 20 mm wide treated band, which helps to prevent the overlapping. A graphite spray was used to improve the absorption of the laser beam. Defocus was 84 mm, except for sample 12 and sample 14.

The applied laser parameters for the hardening experiments can be seen in Table 2.

Table 2. Laser hardened test specimens (with sample numbers 11-18), and the experimental parameters

| Feed speed (mm/min) | Laser power (kW) |
|---------------------|------------------|
|                     | 2.8  | 3.4  | 3.8  | 4.5  |
| 200                 | 18   | 17   |      |      |
| 250                 |      |      | 16   | 15   |
| 300                 |      |      |      | 11, 12*, 14** |
| 400                 |      |      |      | 13   |

* 130 mm defocus, ** 100 mm defocus
3. Results and discussion

3.1. Metallography

In the following, two representative laser hardened specimens will be introduced (with sample number 11 and 17). The metallographic images were taken by a Keyence VHX2000 digital optical microscope (Figures 4, 5).

![Figure 4. Metallographic image of sample 11 (etched in 5% Nital solution)](image)

![Figure 5. Metallographic image of sample 17 (etched in 5% Nital solution)](image)

The amount of martensite were significant in both samples, and both the dark and light coloured matrix surrounding the microstructural elements was martensitic, as shown in Figure 6. The surface of sample 17 was melted. For a more exact investigation, sample 17 was over-etched to give a better view of the microstructural structure (Figure 6).

![Figure 6. Over-etched metallographic image of sample 17 (etched in 5% Nital solution)](image)

The over-etched image shows that the light colour matrix was indeed (spiky) martensitic, which was more difficult to etch due to its high carbon content. This produces a higher compressive stress than the dark spiked martensite because of its higher carbon content. In some parts near the surface the sample was melted, for example along the former austenite phase boundaries, and ledeburite.
crystallized from the melt. (Ledeburite is the eutecticum of carbon and iron. It consists of cementite and pearlite microstructural elements.)

3.2. Residual stress analysis by X-ray diffraction

The principle of diffraction analysis is that residual stress - from a crystalline point of view - results in the change of the lattice parameter. Residual stress can be calculated by measuring the changes in the distance of the lattice plates in the material.

The test was performed by a Cr X-ray tubed Stresstech Xstres 3000 G3R X-ray diffractometer and an XTronic software. The values were calculated from the shift of ferrite {211} reflection. The measurements were carried out in 3-3 tilt position (45°-45°) of the goniometer. The exposure time was 10 seconds and the beam spot diameter was 3 mm.

Residual stress values were measured outward from the centre of the treated band (Figure 7, Table 3).

![Figure 7. Average residual stresses of the samples (+ represents tensile, - represents compressive stress)](image)

| Distance from the centre of the band (mm) | Shot peened sample | Sample 11 | Sample 17 |
|------------------------------------------|--------------------|-----------|-----------|
| 0                                       | -386.1             | -285.7    | -79.9     |
| 4                                       | -292.8             | -374.3    | -95.6     |
| 8                                       | -379.1             | -265.1    | -159.0    |

The character of the stress distribution is not comparable in the case of two LASER hardened samples due to the surface melting of sample 17. On the other hand, taking into account that sample 11 was not melted by the beam, the measured values can be compared to that shot peened one. Based on the measured values, in sample 11, the compressive stress is as high as obtained by shot peening technology (~300-400 MPa).

4. Conclusion

According to the metallography, there were no cracks in the laser beam hardened samples, and a significant amount of martensite phase was formed in both samples.

The effective compressive stress for increasing the fatigue limit is 300-400 MPa. In sample 11, a similarly high compressive stress (300-380 MPa) was achieved.
Although metallographic examinations showed that sample 17 contained the more high-carbon content martensite (which was expected to produce higher compressive stress), it still has much lower compression stress than sample 11. This is explained by the fact that sample 17 had too high energy input during laser beam treatment, which resulted in melting. There were more ledeburite grains in the surface layer and the former austenite phase boundaries were visible. The melt produced tensile stress when cooled, which is contrary to the desired effect.

Therefore, it is advisable to select laser beam parameters for the optimum: producing the highest energy input while avoiding surface melting.

Our study shows that laser hardening can be a good alternative of the conventional technologies - like shot peening and cold rolling - used for increasing the fatigue limit. Laser technology has the advantage of being highly productive and controllable, and also enables to treat hard to reach areas. We plan to test our theory further by submitting the samples to fatigue tests.

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