Optimization of laser surface melt-hardening on gray and nodular iron
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Abstract

Laser surface melt-hardening has recently been successfully introduced into industry to improve the wear resistance of different parts made from gray and nodular irons. A characteristic of this procedure is rapid heating of a thin surface layer of the workpiece material above the melting point temperature. After the completion of heat treatment, a structure-modified surface layer is obtained consisting of the remelted and hardened layer. Experimental results of the study of laser surface melt-hardening process have confirmed that the procedure is suitable also for low-power CO₂ laser sources to increase the depth of the modified layer. Because of remarkable repeatability of the characteristics of the modified layer, it is possible to optimize the process on the basis of experimental data.

1 Introduction

The procedure of laser heat treatment by surface remelting has recently been increasingly used on products from gray and nodular irons for modifying the surface layer [1-4]. Since in laser treatment the surface layer is heated above the melting temperature, greater depth of the austenite transformation in the material is achieved, which contributes to the formation of a modified layer deeper than that obtained by conventional hardening procedures. Thus, laser surface melt-hardening procedure can be successful even when using laser sources with relatively low power. The wanted surface layer cooling rates can be quite easily achieved by rapid heat transfer into the remaining part of the cold mass. In this way, in the upper part of the surface remelted layer, a fine-grained and very hard ledeburite microstructure is created and below in hardened layer it results mainly martensitic microstructure.
2 Experimental procedure

For the experimental surface melt-hardening we used a CO₂-laser with a Gaussian power distribution having a maximum power of 650 W which can be suitably adjusted. The experiments were made at a laser source power of 450 W, defocusing degree 10 mm and focal length of the lens 63.5 mm.

In the tests, different qualities of gray and nodular irons were used, having different heat conductivities because of different graphite morphology and matrix structure. The chemical composition, graphite content and matrix structure of the particular irons can be found in Table 1.

<table>
<thead>
<tr>
<th>Basic data</th>
<th>Material (ISO)</th>
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<tbody>
<tr>
<td></td>
<td>Grade 200</td>
</tr>
<tr>
<td>C (%)</td>
<td>3.40</td>
</tr>
<tr>
<td>Si (%)</td>
<td>1.95</td>
</tr>
<tr>
<td>CE (%)</td>
<td>4.08</td>
</tr>
<tr>
<td>Graphite (%)</td>
<td>12.88</td>
</tr>
<tr>
<td>Matrix structure</td>
<td>Pearlite</td>
</tr>
<tr>
<td>Heat conductivity (W/mK)</td>
<td>31</td>
</tr>
</tbody>
</table>

Figure 1 shows the laser beam trace in longitudinal (A) and traverse (B) direction on the sample and the sample dimensions.
An additional requirement in the given melt hardening conditions was a 30% overlapping of remelted traces and a required depth of the modified layer which ranged within 0.4 - 0.5 mm. Thus, in the case of gray iron we decided on the travelling speed $v_b = 24$ mm/s with an energy input of $E = 16.5$ J/mm$^2$, and in the case of nodular iron on $v_b = 12$ mm/s with an energy input of $E = 33$ J/mm$^2$. The dimensions of the samples were adapted to the chosen surface melt-hardening procedure and the requirements of subsequent residual stress measurements.

3 Experimental results

3.1 Microstructure analysis

Figure 2 shows two metallographs of the modified layer cross-sections of gray and nodular irons, where it is possible to distinguish three main zones:

a) Basic - unmodified material.

b) Hardened layer:
   - In nodular iron consisting of martensite, residual austenite, ferrite and graphite nodules surrounded by martensitic shells.
   - In gray iron consisting of martensite, residual austenite and flake graphite.

c) Remelted layer:
   - Consisting of austenite dendrites, ledeburite, individual coarse martensite needles and some undissolved graphite.

![Figure 2: Cross-section of the laser modified layer.](image)
3.2 Microhardness analysis

The measurements of microhardness have proved the success of laser surface melt-hardening method and confirmed the structural changes in the material. Figure 3 shows the microhardness profile for gray iron Grade 200 after surface melt-hardening at a sample speed of 24 mm/s and for nodular iron 400-12 at a sample speed of 12 mm/s. In the gray iron, the microhardness is a bit higher in the surface of the remelted layer and is then gradually falling due to a reduced amount of carbon or cementite in the ledeburite. In the nodular iron, due to reduced carbon concentration in the remelted layer, the microhardness too is lowered. The microhardness in the hardened layer is very uniform since the microstructure is very homogeneous consisting of martensite, residual austenite and graphite flakes in gray iron and martensite, residual austenite, ferrite and graphite nodules surrounded with hard shells in nodular iron. Hard shells around the graphite nodules in nodular iron have a martensite microstructure with microhardness between 800 and 900 HV<sub>100</sub>.

![Microhardness profile in the modified layer.](image)

a) Gray iron, \( v_b = 24 \text{ mm/s} \)

![Microhardness profile in the modified layer.](image)

b) Nodular iron, \( v_b = 12 \text{ mm/s} \)

Figure 3: Microhardness profile in the modified layer.
3.3 Selection of optimal sample travelling speed

For making decisions in determining the optimal conditions we worked out a set of descriptive evaluation criteria regarding the condition of the remelted layer, hardened layer and the surface. In this way we were able to define the highest and lowest possible sample travelling speed which will still ensure a sufficient thickness of the modified layer of acceptable quality. The optimization of the laser melt-hardening process has to be performed for the lamellar and nodular iron separately. The descriptive criteria to evaluate the heat treatment are shown in diagrams in Figure 4, i.e.:

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>GRAY IRON Grade 200</th>
<th>NODULAR IRON 400-12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Defects in remelted zone</td>
<td>Furrows</td>
<td>Porosity and Cracks</td>
</tr>
<tr>
<td>Microhardness</td>
<td>High</td>
<td>Good quality</td>
</tr>
<tr>
<td>Modified layer depth</td>
<td>Increasing</td>
<td>Too low</td>
</tr>
</tbody>
</table>

Figure 4: Optimization of laser surface melt-hardening process.

1. The quality of the surface of the modified layer: On the surface of gray iron, at the sample travelling speeds bellow 16 mm/s an occurrence of furrows can be noted. The surface of the modified layer on the nodular iron is smooth in the range of sample travelling speeds that were used in the experiment.

2. Microstructure analysis: In gray iron, the occurrence of porosity and cracks in the remelted layer can be noted at all sample travelling speeds. They are treated as defects. In nodular iron we can note some undissolved graphite nodules caught on the surface of the remelted layer. Their number increase with sample travelling speeds. In cases, when we use such surfaces with undissolved graphite nodules in wear applications, we do not take them as defects, but as a solid lubricant.

3. Microhardness analysis: Surface melt-hardening achieves good microhardness profiles across the modified layer on gray and nodular irons at all sample travelling speeds.
4. Modified layer depth analysis (Fig. 5): The depth of the modified layer is lower than 0.3 mm as early as at energy input lower than 16 J/mm², that means at sample travelling speeds higher than 30 mm/s in gray iron and at energy input lower than 22 J/mm² (at sample travelling speeds higher than 25 mm/s) in nodular iron. In nodular iron we can also clearly see that at energy input higher than 60 J/mm² (at sample travelling speeds lower than 8 mm/s) the modified layer depth does not increase any more.

On the basis of the assessed criteria we defined, for gray iron, the optimal sample travelling speeds to be in a range within 18 and 30 mm/s. In these laser surface melt-hardening conditions it is achieved that the modified layer depth does not fall below 0.3 mm while at the same time the surface of the modified layer itself is rather smooth and without any furrows. In the case of nodular iron the optimal sample travelling speeds are in a range within 8 and 25 mm/s. Since the microstructures on the particular layers did not display too many irregularities, we can choose the appropriate sample travelling speed on the basis of the demanded depth for the modified layer.
3.4 Residual stress analysis

In this study the identification of residual stresses was based on the relaxation method, which consisted in measuring sample deformation. The relaxation was induced by electro-chemical removal of the stressed surface layer, causing a breakdown in the existing equilibrium state.

The residual stress variation is very much dependent on the conditions present in the process of remelted layer cooling which can be described by the volume percentage of residual austenite and cementite and concentration gradient of the carbon. With the increase of the amount of residual austenite in the remelted layer, there is a great danger that residual stresses will change the direction and will transform from compressive into tensile. A surface with tensile residual stresses is, however, much more likely to develop cracks, which may propagate and grow into a catastrophic failure.

In Figures 6 and 7 we can see the variation of residual stresses as a function of the depth of the modified layer for gray iron Grade 200 and for nodular iron 400-12. Both figures present two measured curves, that is:
- the full line presents the measured residual stress for the specimen heat treated with a zig-zag laser beam path in longitudinal direction,
- the dashed line presents the measured residual stress for the specimen heat- treated with a zig-zag laser beam path in traverse direction.

From the two graphs we can conclude the following:

1. Residual stresses have a very similar profile differing only in absolute values. In all cases and in heat treatment of all irons tensile residual stresses were found on the surface varying from 100 - 300 N/mm².

2. The change from tensile into compressive residual stress takes place in the area between 0.05mm to 0.1mm. Maximal compressive residual stresses are found in the range between 0.2 mm to 0.3 mm and then increase very slightly to the depth of 0.55 mm or 0.65 mm.

3. It is in the nodular iron 400-12 that compressive residual stresses are highest and amount even up to 500 N/mm² in the depth around 0.3 mm. In general, it can be stated that different nodular iron qualities reach the highest residual tensile stresses on the surface and also the highest residual compressive stresses below the surface depending of course on the quality of the nodular iron.

4. Worth of attention are very high residual stresses occurring during specimen cooling, as the metallographical analysis of the remelted layer revealed longer or shorter cracks of random direction. Our assessment is that during the cooling process, due to high temperature differences, extremely high tensile residual stresses were generated, exceeding the yield
point of the material in the remelted surface layer. Thus the material cracked in the direction of graphite flakes in the gray iron. Although the nodular iron was heat treated at lower sample travelling speeds than the gray iron, it is our opinion that it is especially the shape of the graphite that is decisive for the occurrence of cracks during the cooling process.

5. Gray iron retains less residual stresses after cooling especially because of its pearlite matrix and good solubility of graphite flakes in the austenite. These two ensure good homogenization of carbon in the remelted and hardened layer and therefore also lower residual stresses. The nodular irons of different qualities have a ferrite-pearlite or pearlite-ferrite matrix which in rapid cooling or heating does not grant homogenization either in the remelted or hardened layer. This results in big differences in residual stresses already during cooling process as well as after cooling process. Thus in our estimation the prevailing stresses are especially residual stresses between the particular crystal grains but there are also big differences in the magnitude of micro residual stresses on different places inside crystal grains on the microscopic level, which however our measurement did not reveal.

6. Due to high roughness of the remelted layer surface it is in all cases necessary to apply fine-grinding. Fine-grinding can remove only a thin surface layer of some micrometers into the depth of the specimen, which means that the tensile residual stress state is still maintained in the surface layer. Although the procedure is very interesting for surface hardening of different kinds of gray and nodular irons, the presence of tensile residual stresses in the remelted layer is a great disadvantage since the treated components are subject to crack occurrence that may even lead to failure.

Figure 6: Residual stresses in samples of gray iron Grade 200 after melt-hardening, sample travelling speed $v_b = 24$ mm/s.
4 Conclusions

On the basis of the results of microstructure and microhardness analysis on the studied irons, it can be concluded that laser surface melt-hardening can be regarded as a highly successful method for increasing the hardness and wear resistance of gray and nodular irons. Great attention has to be given to the selection of optimal laser melt-hardening conditions as different structure of the microstructure matrix and the size and shape of graphite can substantially affect the thermal conduction of the material. Experimental results have confirmed that surface melt-hardening can be successfully performed also with low power laser sources. They achieve a sufficient depth of the modified layer, desirable microstructure changes and good microhardness profiles accross the modified layer.

After laser surface melt-hardening of different kinds of gray and nodular irons the measured residual stresses show a similar variation as well as absolute values at different sample travelling speeds and at different kinds of guiding the laser beam across the surface. Residual stresses are in all the cases of tensile type on the surface and then slightly decrease to the depth of 0.1 mm or 0.2 mm when they transform into compressive stresses. The relatively great depths of transformation of tensile into compressive residual stresses confirm that even after fine-grinding it is no possible to achieve the desired stress state in the material with more or less high compressive residual stresses on the surface. The results of the research investigation confirm that especially gray iron components, as well as nodular iron components, have to be very carefully designed and carefully machined by grinding in order to avoid notch effects or ultimate failure.
5 References