The influence of non-metallic inclusions on the strengthening of steels by laser treatment

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Abstract

Structural changes in steels matrix near different non-metallic inclusions were investigated. The influence of these changes on the structure and strength of inclusion-matrix boundaries and also on the mechanism and parameters of the microcrack formation near non-metallic inclusions is shown.

1 Introduction

Steels contain non-metallic inclusions, which influence on the character of strengthening during laser quenching. In process of treatment non-metallic inclusions can melt, fully or partly or remain solid. In spite of short-term treatment, energy of the laser ray turn out sufficient for melting of the highly melt and light melt inclusions, and also for the development of mass transfer processes, which leads to enrichment of steel matrix elements of inclusions and transfer of matrix elements to the surface zone of inclusions. In the matrix near inclusions relationally processes occurred, included speed local shear-rotational deformation and elements of the return and recrystallization.

The character of steels strengthening depends on the types of non-metallic inclusions and matrix, and also speed transformations, which flow in the matrix, phase, deformation and high temperature hardening, dissolve of the carbides, micro chemical inhomogeneity. The goal of this investigation was to establish the influence of the non-metallic inclusions on the structural changes in steel matrix and in the inclusion-matrix boundaries by laser treatment and also the influence of this changes on the behavior of the non-metallic inclusions during plastic deformation.
2 Materials and procedures

Specimens made of wheel steel, 08Yu, 08T, 08Kp, 08Ch18N10T, ShCh15, 12GS were irradiated by a laser in GOS-30M installation with an excitation voltage of 2.5kV and a pulse energy of 25J (at a hearing rate of $10^5 \frac{\text{C}}{\text{s}}$ and a cooling rate of $10^6 \frac{\text{C}}{\text{s}}$, with an action time of $10^3 \text{s}$). Non-metallic inclusions were identified by metallographic, X-ray micro spectral, and petrographic methods. After laser treatment specimens were subjected to tensile tests in IMASH-5S and “Plastometr UZTM” installations in the temperature range 25-1250°C at strain rates of 0.5-50s⁻¹. Sizes of inclusions and micro damages were determined by the method of quantitative metallography. Micro cracks were studied with “Neophot-21” and “Stereoskan-S4” microscopes.

3 Results and discussion

In the laser strengthening zone of steels there are some defects, among them related to non-metallic inclusions: structural unhomogeneity (fig. 1a), brittle cracks and voids (fig. 1b), geometrical disruption of strengthening case, sections of oxidation (fig. 1c). During laser treatment there are some alterations in non-metallic inclusions and in steel matrix. The laser radiation is unhomogeneity in section, as well as the temperature field, because in treatment zone we can see the areas with melting and without melting.

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The behavior of the non-metallic inclusions in steels under laser treatment depend on their type.

High melting non-metallic inclusions (oxides $\text{Al}_2\text{O}_3$, $\text{Cr}_2\text{O}_3$, $\text{SiO}_2$, $\text{TiO}$, $\text{MnO}.\text{Al}_2\text{O}_3$, $\text{MgO}.\text{Al}_2\text{O}_3$, $\text{MnO}.\text{Cr}_2\text{O}_3$, $\text{TiCN}$ and other) are melted on surface or remain solid during laser treatment (Fig. 2). Low melting non-metallic inclusions (silicates $\text{MnO}.\text{SiO}_2$, $\text{FeO}.\text{SiO}_2$, sulfides $\text{FeS}$, $\text{FeS}.(\text{Mn},\text{Fe})\text{S}$, $(\text{Mn},\text{Fe})\text{S}$) during laser treatment

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Figure 1. Defects near non-metallic inclusions in laser treatment zone of steels; x200
are melted and spread over a surface under shock wave (Fig. 3). The components of inclusions penetrated into steel matrix and saturate it (Fig. 4).

Figure 2. Highmelting non-metallic inclusions TiCN (a), Al₂O₃ (b) and SiO₂ (c) after laser treatment; x500

Figure 3. Lowmelting non-metallic inclusions MnO₃SiO₂ (a), FeS-(Mn,Fe)S (b) and (Mn,Fe)S (c) after laser treatment; x500
Steel matrix near non-metallic inclusions is strengthened, its micro hardness increased; the degree of strengthening depends on the type and state of inclusion and steel matrix in the course of treatment (table 1). The value of factor \( K_s \) is determined the contribution of non-metallic inclusions into the steel matrix strengthening.

<table>
<thead>
<tr>
<th>Inclusion</th>
<th>State of inclusion</th>
<th>Steel</th>
<th>State of matr.</th>
<th>( H_{\text{matr.}} ), Mpa</th>
<th>( H_{\text{matr. inc}} ), Mpa</th>
<th>( K_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiN, TiCN</td>
<td>sol., melt., surf.</td>
<td>08T</td>
<td>liq.</td>
<td>280</td>
<td>510</td>
<td>1,82</td>
</tr>
<tr>
<td>FeO-TiO₂</td>
<td>melt., surf.</td>
<td>08Ch 10</td>
<td>liq.</td>
<td>275</td>
<td>512</td>
<td>1,86</td>
</tr>
<tr>
<td>TiO</td>
<td>sol.</td>
<td>08T</td>
<td>liq.</td>
<td>280</td>
<td>440</td>
<td>1,57</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>melt., surf.</td>
<td>08Ch 10</td>
<td>liq.</td>
<td>256</td>
<td>458</td>
<td>1,79</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>sol., melt., surf.</td>
<td>08Yu</td>
<td>soļ, liq.</td>
<td>286</td>
<td>452/518</td>
<td>1,58, 1,81</td>
</tr>
<tr>
<td>MnO●Al₂O₃</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MnO●SiO₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>sol.</td>
<td>08</td>
<td>liq., soļ</td>
<td>260</td>
<td>437/395</td>
<td>1,68, 1,52</td>
</tr>
<tr>
<td>(Fe,Mn)S</td>
<td>liq.</td>
<td>wheel</td>
<td>liq., soļ</td>
<td>600</td>
<td>912</td>
<td>1,52</td>
</tr>
<tr>
<td>FeS- (Fe,Mn)S</td>
<td>liq.</td>
<td>wheel</td>
<td>liq., soļ</td>
<td>600</td>
<td>1002/936</td>
<td>1,67, 1,56</td>
</tr>
<tr>
<td>MgO●Al₂O₃</td>
<td>melt., surf.</td>
<td>StCh15</td>
<td>liq.</td>
<td>234</td>
<td>372/404</td>
<td>1,59/1,73</td>
</tr>
</tbody>
</table>

During the analysis of the investigation results we should take into account the peculiarities of laser treatment (the significant laser impulse, the high radiation energy density, the transitory of treatment, high heating and cooling rates, which promotes the high rate of structural and phase transformations. Laser impulse influence is similar to explosion. In shock waves of the huge pressure initiation, which take place the plastic relaxation and original mass transfer mechanism. Based on results, there is multiplication of dislocations and vacancies, dislocation reactions, formation of dislocation steps. Also there is increase in the quantity of sliding and twinning systems. In steel matrix near non-metallic inclusions high rate plastic relaxation (fig. 5a) takes place; and it is possible high-speed recrystallization with formation of elongated grains around inclusions (fig. 5b).
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The process of laser strengthening of steels near non-metallic inclusions is defined by a few factors:

$$\sigma = \sigma_{\text{hard}} + \sigma_{\text{phase-hard}} + \sigma_{\text{all}} + \sigma_{\text{chem}} + \sigma_{\text{term}} + \sigma_{\text{def}} + \sigma_{\text{recr}}$$

- $\sigma_{\text{hard}}$: strengthening by high temperature hardening;
- $\sigma_{\text{phase-hard}}$: strengthening by structural strain hardening;
- $\sigma_{\text{all}}$: strengthening by dissolution of carbides and micro alloying;
- $\sigma_{\text{chem}}$: strengthening by micro chemical unhomogenity;
- $\sigma_{\text{term}}$: strengthening by heat stresses on the inclusion-matrix boundaries and in matrix near inclusions;
- $\sigma_{\text{all}}$: strengthening by partial dissolution of inclusions and micro alloying of steel matrix;
- $\sigma_{\text{def}}$: strengthening by plastic relaxation;
- $\sigma_{\text{recr}}$: strengthening by local return and recrystallization.

Laser treatment can influence on the mechanism of micro damages formation during plastic deformation of steels. Since between non-metallic inclusions and steel matrix the interaction take place during laser treatment, the influence of this process on the interphase boundaries behavior was investigated. There are some non-metallic inclusions (Al$_2$O$_3$, spinels, some sulfides), which inclined to voids or tough cracks formation by decohesion of inclusion-steel matrix boundaries during plastic deformation (fig. 6a). Those non-metallic inclusions are badly wetting by liquid steel and there are micro voids on the inclusion-matrix boundaries. Silicates, nitrides and carbonitrides of titanium, some sulfides, which are well wetting by liquid steel have conjugated inclusion-matrix boundaries and inclined to brittle cracks formation in inclusions. After laser treatment in deformed specimens the voids were not discovered. Near all types of inclusions brittle separations were shown on the inclusion-matrix boundaries (fig. 6b, c, d).
Figure 6. The micro damages near non-metallic inclusions: a - Al₂O₃, void without laser treatment; b - MnO·Al₂O₃, brittle separation of inclusion-matrix boundary, c - FeS-(Fe,Mn)S, brittle separation of inclusion-matrix boundary and d - MnO·SiO₂, brittle separation after laser treatment and plastic deformation by tension; x500

Laser treatment can influence on the parameters of micro damages formation and their development near non-metallic inclusions during plastic deformation. The voids near non-metallic inclusions after plastic deformation without laser treatment formed at smaller critical deformation degree than brittle separations on the inclusion-matrix boundaries after laser treatment and plastic deformation (fig. 7). The inflections of curve are bound with polymorph transformations in steel matrix. The brittle separations after laser treatment and plastic deformation formed at bigger critical deformation degree than brittle cracks in non-metallic inclusions.

Figure 7. Influence of the deformation temperature on the critical deformation degree for micro damages formation near non-metallic inclusions: a - Al₂O₃ in steel 08Yu (cur. 1 - after laser treatment and plastic deformation, cur. 2 - plastic deformation without laser treatment); b - (Fe,Mn)S in wheel steel (cur. 1 - for brittle separations on the phase boundaries after laser treatment and plastic deformation, cur. 2 - for brittle cracks in inclusions after laser treatment and plastic deformation, cur. 3 - for voids after plastic deformation without laser treatment, cur. 4 - for cracks near inclusions after laser treatment and plastic deformation

Brittle separations on the inclusion-matrix boundaries grow most quickly then voids at all temperatures (fig. 8). The further deformation promotes the development of micro damages from inclusions to the steel matrix. In steel matrix near non-metallic inclusions the new cracks appear and the critical deformation degree for them is the highest (fig. 7b).
Figure 8. The change of void diameter $D$ and crack or separation length $l$ with deformation degree increase: a – for inclusions $\text{Al}_2\text{O}_3$ in steel 08Yu (cur. 1,2 – for separations, after laser treatment and plastic deformation, cur. 3,4 – for voids, after plastic deformation without laser treatment, cur. 1,3 – deformation temperature $20^\circ\text{C}$, cur. 2,4 – deformation temperature $900^\circ\text{C}$), b – for inclusions (Fe,Mn)S in wheel steel (cur. 1,2 - brittle separations on phase boundaries, after laser treatment and plastic deformation, cur. 3,4 - voids, after plastic deformation without laser treatment, cur. 1,3 – deformation temperature $20^\circ\text{C}$, cur. 2,4 – deformation temperature $900^\circ\text{C}$)

So, in laser treatment zone the deformation localization near non-metallic inclusions promoted formation of micro damages. The laser radiation promoted brittle cracks and separations formation in the inclusion-matrix boundaries in steels. The atomic exchange across inter phase boundaries and plastic splashes in this boundaries during laser treatment changed the state and structure of inclusion-matrix boundaries (fig. 9). This results in the improvement of coherent conjugation and increase of adhesion on the inter phase boundaries as a result of local micro welding. The influx of elements on this boundaries promoted of strengthening because hampered the relaxation processes, which able to decrease of internal tension stresses component on inclusion-matrix boundaries. The cohesive strength of the non-metallic inclusion-steel matrix boundaries increases.

Figure 9. The structure of inclusion-matrix boundaries before (a) and after (b) laser treatment; x100000

4 Conclusions

The peculiarity of non-metallic inclusions consist of the local matrix saturation by components of inclusions, localization of phases and structural transformation in matrix, also development inter phase stresses on the inclusion-matrix boundaries and in the matrix near inclusions owing to distinction of extension (compression) coefficients of the matrix and inclusions. All inclusions contribute essential deposit to strengthening of steel, however they cause micro unhomogeneous distribution of stresses in the matrix and character of steel strengthening by laser quenching.
During plastic deformation after laser treatment discovered the appearance of local diffusional micro welding of the inclusions with steel matrix, lead to change of the state of inter phase boundaries and mechanism of the micro cracks formation near non-metallic inclusions, also raised of the crack endurance of steel.