TRANSFORMATION OF NON-METALLIC INCLUSIONS “EUTECTICS” IN STEELS UNDER LASER ACTION

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Abstract. Melting and crystallization of heterophase non-metallic inclusions “eutectics” was investigated. Mechanism of melting of the eutectic inclusions and inclusion-matrix boundaries under contact laser melting with steel matrix in the conditions of abnormal mass transfer connecting with formation of zones with high dislocation density and also with electron and electro-magnetic interaction between inclusion and steel matrix was proposed. That allows to create the possibilities for the influence on the inclusion-matrix boundaries and also on the chemical and phase composition of surface layer of non-metallic inclusions. Peculiarities of structure of non-metallic inclusions after speed crystallization were investigated. It was shown that under laser action the initial composite colonial structure of inclusions transits into abnormal eutectic structure. Also it was shown that under laser action the initial structure of inclusion-matrix boundaries transits into unstable equilibrium high-energy condition that cause development of the dissipation processes connecting with aspiration of system inclusion-matrix to the state with minimum of the free energy. In the result of the system eutectic inclusion-matrix transits to the state of unstable equilibrium which determines structure and properties of laser-quenched interphase boundary. Processes of melting, fusion and dissolution of non-metallic inclusions “eutectics” and also of the melting of steel matrix play the great role in transformation of interphase inclusion-matrix boundaries under laser action.

KEYWORDS: NON-METALLIC INCLUSIONS “EUTECTICS”, STEEL, STRENGTHENING, LASER TREATMENT

1. Introduction.
In steels, heterophase types of inclusions are often present [1 - 7]. For heterophase inclusions, the presence of internal interphase boundaries is characteristic, which, along with the inclusion-matrix interphase boundaries, play an important role in the formation of defects, which is very important when analyzing the reliability and durability of products operating in different conditions [4, 8 - 11]. Heterophase inclusions of the “eutectics” type are formed as a result of simultaneous crystallization of the phases during eutectic transformation. Such inclusions have a eutectic structure and are colonies of eutectic phases eu1 and eu2 — composite formations of different types depending on the composition and nature of these eutectic phases (Fig. 1), although conglomerates of eutectic phases are possible. Accordingly, it is possible to designate the interphase boundaries inclusion-matrix eu1→m and eu2→m. Eutectic inclusions with phases eu1 and eu2: sulfide FeS-MnS, FeS-(Mn, Fe)S, FeS-Al2S3, (Fe, Mn)3S-FeS, (Fe, Cr, Mn)S-FeS, (Fe, Cr, Mo)S-(Fe, Mn)S, nuxysulfide FeS-FeO, MnS-MnO, MnO-FeS, (Fe,Mn)O-(Fe, Mn)S, (Fe, Mn Cr)S-FeO, oxide MnO-Mn2O3, Fe2O3-CaO-Fe2O3, MgO-Al2O3-2MgO-SiO2, MgO-Al2O3-2MgO-Al2O3-MgO, 3CaO-Al2O3-CaO-Al2O3, CaO-Al2O3-CaO-2Al2O3, CaO-Al2O3-CaF2, silicate FeO-SiO2-MnO-SiO2, 2FeO-SiO2-MnO-SiO2, 2FeO-SiO2-CaO-MgO-SiO2, FeO-SiO2-CaO-FeO-SiO2, 2CaO-Al2O3-SiO2-CaO-MgO-SiO2, CaO-FeO-SiO2, nitride TiN-TiCN, sulfosilicate Fe2O-SiO2, oxinitrite FeO-FeO · SiO2. In the structure of such inclusions, due to the joint crystallization of the phases, a certain regularity is observed in their arrangement, typical of eutectics, although phase conglomerates are possible, and the second phase can form layers with an oval cross section or films along the grain boundaries of the first phase.

The goal of this investigation was to research the processes of melting, dissolution, crystallization of the heterophase non-metallic inclusions “eutectics” in hyper-nonequilibrium conditions and the influence of these inclusions on the peculiarities of structural changes in steel matrix and its strengthening under laser treatment.

Specimens made of wheel steel R7, 08Yu, 08T, 08Kp, 08Ch18N10T,ShCh15, NB-57, 12GS, E3 were irradiated by laser in GOS-30M installation with an excitation voltage of 2,5kV and pulse energy of 10, 18, 25 and 30J at heating rate of 10^5 °C/s and cooling rate of 10^6 °C/s with action time of (1,0, 2,5, 3,6, 4,2 и 6,0) 10^-5 s. Heterophase non-metallic inclusions “phases are beside” were identified by metallographic, X-ray microspectral and petrographic methods, [1, 12]. Distribution of elements and nanohardness of steel matrix near inclusions were determined.

3. Results and discussion.

Figure 1. Non-metallic inclusions “eutectics” before laser action; x6000
Most of inclusions of “eutectics” are low-melting and both their phases must to melt almost simultaneously. But eutectics with high-melting phases exist too [1, 4]. Inclusions of eutectics are differed from heterophase non-metallic inclusions “high-melting phase surrounding with low-melting cover” and “phases are beside” with the presence of more dispersed phases and more branching net of interphase boundaries eu1↔eu2 inside inclusions. Molten inclusions “eutectics” is been in molten steel matrix and micrometallurgical bath is formed. Hydrodynamics flows in the conditions of vortex thermocapillary mixing and temperature gradients are origins and that causes displacement of inclusion phases. In the result of high-speed melting of inclusions “eutectics” heavy oversaturated liquid solution or two liquid solutions on the base of inclusion and steel matrix differing by concentration heterogeneity are formed. In such liquid systems nonbalanced mass transfer is happened that suppresses of cooperative growth of phases and formation of cooperative structures of non-metallic inclusion.

Evidently under laser melting and contact interaction of eutectic inclusion with liquid steel matrix advantageous the dissolution (melting) of interphase boundaries eu1↔eu2 must to happen. Just distribution of surface tensions in the zone of contact interaction when heavy disordered state in surface areas of eutectic phases is created and diffusive composition equalizing do not happened the heavy nonequilibrium conditions and thermodynamic stimulus for rapid simultaneous or selective dissolution of phases of inclusion are appeared. Besides since speed of mass transfer and degree of saturation of eutectic phases with elements of steel matrix (in first turn with iron) is different. That phase of inclusion with more degree of saturation by iron is dissolved more quickly.

Inclusions of “eutectics” containing both low-melting and high-melting phases after high-speed crystallization in the conditions of laser action were investigated. They had regular colony structure in the initial state. In the most of them such structure was not kept after laser action. Evidently transformation of type of eutectic was happened. Regular colony structure was transformed into abnormal eutectic without regular distribution of components (Fig. 2, a - d). In such inclusions no regular distribution of the elements of the eutectic phases is observed (Fig. 3, a). According to reference [5], abnormal eutectics are formed in conditions when conjugal growth of crystals of eutectic phases do not possible and also when eutectic is formed with high-entropy phases. It is evidently the absence of possibility for conjugal growth of crystals of eutectic phases in the conditions of laser action. For the structure of abnormal eutectics the presence of phase areas with different shape chaotically disposing in inclusion is typical. Abnormal eutectic structures after laser action with energy of impulse $W_{\text{pulse}} = 10 - 25$ J were observed. In the resort of $W_{\text{pulse}} = 30$ J together with abnormal eutectics the sulphide and silicate eutectics inclusions with amorphous structure were observed (Fig. 2, e), which have significant chemical heterogeneity (Fig. 3, b). As a rule, these were sulphide or silicate eutectics, i.e. inclusions consisting of fusible phases. Some inclusions have signs of colony structure (Fig. 2, f). Various of structures of inclusions of “eutectics” is explained with differences of nature of eutectic phases and also with heterogeneity of laser radiation promoting appearance of different conditions of their crystallization. Steel matrix under laser melting is saturated with elements of phases of inclusions of “eutectics” independently on the type of inclusion.

**Figure 2.** Dissolution and melting of heterophase non-metallic inclusions of “eutectics” under laser action; x2000

![Figure 2](image_url)
In anomalous eutectic inclusions, the interphase boundaries of eu1↔eu2 inclusions appear somewhat “blurred”; X-ray microscopic analysis showed that the content of elements of the neighboring phase in both phases of inclusion was increased near these boundaries (Fig. 3, a). This indicates the mutual exchange of atoms between the inclusion phases at the moment of eutectic melting, which occurs through their disordered transitions across the eu1↔eu2 boundaries, as well as through the boundaries with the molten steel matrix. Considering the features of laser melting of two-phase inclusions of “eutectic”, it should be noted that each phase of the inclusion contacts both the steel matrix and the other phase of the inclusion, i.e. It has two interphase boundaries (the inclusion-matrix eu1↔m, eu2↔m and the inclusion-inclusion eu1↔eu2), which differ in structure [4].

Contact dissolution and melting of phases eu1 and eu2 of inclusions “eutectics” and also of interphase boundaries eu1↔eu2, eu1↔m, eu2↔m in molten steel matrix in nonequilibrium conditions under laser action is energetically excited because surface layers of both phases of inclusion being in stress state with high energy are replaced with liquid phase with less energy. Decrease of surface energy owing to contact interaction of eutectic phases and steel matrix and also owing to interaction of phases eu1 and eu2 of inclusion in the moment of melting is rather considerably that system “phase eu1 of inclusion” – “boundary eu1↔eu2” – “phase eu2 of inclusion” – “interphase boundaries eu1↔m, eu1↔m” – “steel matrix” was thermodynamics instable after laser action. Realization of such mechanism of melting and dissolution of inclusions of “eutectics” is determined with value of stresses creating in surface layers of both phases of inclusion. Evidently owing to formation of big stresses in surface layers of matrix and both phases of inclusion “eutectics” in the conditions of high-speed laser action it is possible nonactivated transformation of heavy disordered surface layers of both phases of inclusion into liquid state with formation of liquid phase.

Consistency of formation of heavy disordered areas on the surface layers of both phases of inclusion “eutectics” and also movement of interphase boundaries is shown on Fig. 4. In the moment of melting (dissolution) of eutectic type of inclusions the both their phases must to dissolve practically simultaneously. Evidently owing to contact interaction of inclusions with liquid steel matrix advantage melting (dissolution) of interphase boundaries of eutectics takes place. On Fig. 4 surface tensions on interface boundaries are shown. Distribution of surface tensions in zone of contact interaction then heavy disordered state in surface areas of eutectic phases is formed and diffusive equalizing of composition do not has time for happen the heavy nonequilibrium conditions are created and thermodynamics stimulus for rapid simultaneous or selective dissolution of inclusion phases is appeared.
The results of a study of the distribution of nanohardness in the zones of saturation of the steel matrix adjacent to the phases of eu1 and eu2 inclusions of the "eutectics" type showed that the nanohardness is much higher than its average value for the matrix far from the inclusions (Table 1). The level of nanohardness of each zone of the metal matrix is determined by the type of steel, since the degree of hardening in the process of laser action depends on its composition and structure. In the first saturation zone, the values of \( H_u \) at a pulse energy of 25 J and an exposure time of 3.6 \( \times 10^{-3} \) s at 1.46 ... 1.95 times higher than in the steel matrix far from the inclusion. In the second and third saturation zones, the values of the nanohardness of the steel matrix are lower than in the first zone, but exceed the values of \( H_u \) for the matrix far from the inclusions, respectively, in 1.39 ... 1.58 and 1.29 ... 1.42 times at a pulse energy of 25 J and exposure time 3.6 \( \times 10^{-3} \) sec. Bursts of the nanohardness of the steel matrix were observed, which under the same conditions of laser action in the saturation zones 1, 2, 3 were respectively the excess of the nanohardness of the steel matrix far from the inclusion of 1.75 ... 2.41; 1.61 ... 1.85; 1.55 ... 1.63 times. Obviously, a cascade distribution of the values of the nanohardness of the metallic matrix is observed at a distance from the phases eu1 and eu2 of the inclusion.

Table 1. The values of the nanohardness of the saturation zones of steel matrix near the “eutectic” type of inclusions \( H_u \) and far from them, \( H_m \), as well as the coefficient \( K_i \) at a pulse energy of 25 J and an exposure time of 3.6 \( \times 10^{-3} \) s

<table>
<thead>
<tr>
<th>Inclusion eu1-eu2, steel, ( H_u ), x 10, MPa</th>
<th>Phases of inclusion (state under laser action: ( *L – ) liquid; ( \text{M} – ) melted)</th>
<th>Condition and type of saturation zone in steel matrix of steel matrix under laser action</th>
<th>( H_u ), x 10, MPa and ( K_i ) in zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeS-(Fe,Mn)S, 08Kp, 260</td>
<td>FeS (L)</td>
<td>Liquid; columnar, spotted</td>
<td>379 (1.46); “bursts” 455 (1.75)</td>
</tr>
<tr>
<td></td>
<td>(Fe,Mn)S (L)</td>
<td></td>
<td>429 (1.65); “bursts” 494 (1.9)</td>
</tr>
<tr>
<td>TiN-TiCN, 08T, 280</td>
<td>TiN (M)</td>
<td>solid / liquid; cascade with “bursts”</td>
<td>518 (1.85); “bursts” 616 (2.2)</td>
</tr>
<tr>
<td></td>
<td>TiCN (M)</td>
<td></td>
<td>549 (1.96); “bursts” 675 (2.41)</td>
</tr>
<tr>
<td>FeO SiO2-MnO SiO2, 08Uy, 290</td>
<td>FeO SiO2 (L)</td>
<td>Liquid; columnar, spotted</td>
<td>508 (1.75); “bursts” 600 (2.1)</td>
</tr>
<tr>
<td></td>
<td>MnO SiO2 (L)</td>
<td></td>
<td>574 (1.98); “bursts” 670 (2.31)</td>
</tr>
<tr>
<td>MgO Al2O3-2MgO SiO2, ShH15, 750</td>
<td>MgO Al2O3 (M)</td>
<td>Liquid; cascade with “bursts”</td>
<td>1185 (1.58); “bursts” 1350 (1.8)</td>
</tr>
<tr>
<td></td>
<td>2MgO SiO2 (L)</td>
<td></td>
<td>1343 (1.79); “bursts” 1440 (1.92)</td>
</tr>
</tbody>
</table>

The main factor for strengthening the phase-adjacent type of "eutectics" the steel matrix is its microalloying from internal sources, which are the phases of eu1 and eu2 of nonmetallic inclusion. In this case, by forming local liquidation zones near each inclusion phase, saturation zones of a cascade-type steel matrix are created, which are layered composite regions near the phase differences of nonmetallic inclusions.


The mechanism of melting of inclusions “eutectics” under laser action depends on their type. In this case, as a rule, their composite colonial microstructure is transformed into the structure of anomalous eutectics. Near the heterophase inclusions of the type of "eutectics", the formation of the saturation zones of the matrix is controlled by both phases eu1 and eu2 of inclusions, which are sources of internal doping of the steel matrix. In the vicinity of both phases of inclusions, we observed composite liquidation zones of saturation of a steel matrix of several types. A characteristic feature of the saturation zones of the steel matrix for heterophase inclusions of this type is that near the different phases of the ph1 and ph2 inclusions saturation zones of the matrix with different structures were encountered. Therefore, their Formation of the saturation zones of the steel matrix near inclusions “eutectics” under laser action depends on the behavior of different phases of inclusion, as well as the ability to speed mass transfer of the elements of these phases to the surrounding steel matrix under conditions of pulsed laser action.
5. Literature.