

INFLUENCE OF NON-METALLIC INCLUSIONS ON THE STRENGTHENING OF STEELS UNDER LASER ACTION

ВЛИЯНИЕ НЕМЕТАЛЛИЧЕСКИХ ВКЛЮЧЕНИЙ НА УПРОЧНЕНИЕ СТАЛЕЙ ПРИ ЛАЗЕРНОМ ВОЗДЕЙСТВИИ

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Abstract. Melting and crystallization of non-metallic inclusions in contact with steel matrix during laser treatment was investigated. It was shown that laser action is the method of local change of inclusion structure in the surface fused layers and also of the properties of non-metallic inclusion surface. Peculiarities of steel matrix saturation with elements of non-metallic inclusions during different regimes of laser action were investigated. It was shown the role of that process in the formation of local structure of steel matrix near non-metallic inclusions. That allows to realize possibility of transformation of the non-metallic inclusions how sources of inside local alloying of steel matrix. It was fixed that in local areas of steel matrix the liquation strengthened zones were formed. They represent different types of composite layers: gradiental zones with cascade and "spot" distribution of elements and nanohardness, dispersal zones with different types of microphases and nanophases, "tunnel" zones, and also zones with combine structure. It was shown the role of non-metallic inclusions in development of micro heterogeneous strengthening of steels under laser treatment.

KEYWORDS: NON-METALLIC INCLUSIONS, STEEL, STRENGTHENING, LASER TREATMENT

1. Introduction.

Steels contain non-metallic inclusions which influence on the character of strengthening during laser quenching. In the process of laser treatment non-metallic inclusions are fully or partly melted down or are remained hard, in reference [1]. In spite of short-term treatment the energy of laser radiation turns out sufficient for melting of the high-melting and low-melting inclusions, and also for the development of mass transfer processes which lead to enrichment of steel matrix with the elements of inclusions and also transfer of matrix elements to the surface zone of inclusions. Areas of steel matrix near non-metallic inclusions are the strongly oversaturated solid solution [1]. In steel matrix near non-metallic inclusions the relaxation processes including speed local shear-rotational deformation and elements of return and recrystallization are occurred. The character of steels strengthening depends on the types of non-metallic inclusions and steel matrix, speed transformations which flow in steel matrix. Also it depends on the phase, deformation and high temperature hardening, dissolution of carbides and microchemical heterogeneity. The goal of this investigation was to research the processes of melting, dissolution, crystallization of non-metallic inclusions in hypernonequilibrium conditions and the influence of non-metallic inclusions on the peculiarities of structural changes in steel matrix and its strengthening under laser treatment.

2. Materials and Procedures

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^{-3} s. Non-metallic inclusions were identified by metallographic, X-ray microspectral and petrographic methods [1]. Distribution of elements and nanohardness of steel matrix near non-metallic inclusions were determined.

3. Results and discussion

Under laser action the initial structure of inclusion-steel 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 free energy. In the result of the system 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 and also of the melting of steel matrix play the great role in transformation of inclusion-matrix boundaries under laser action. Probability of melting, fusion and dissolution of inclusions depends on their type. Different non-metallic inclusions after partial or full melting under laser treatment of steels are shown on Fig. 1, 2. Evidently melting of the high-melting inclusions (oxides Al_2O_3 , Cr_2O_3 , SiO_2 , TiO , $MnO \cdot Al_2O_3$, $MgO \cdot Al_2O_3$, $MnO \cdot Cr_2O_3$, $TiCN$) starts in zones being near steel matrix. Low-melting inclusions (silicates $MnO \cdot SiO_2$, $FeO \cdot SiO_2$, sulfides FeS , $FeS \cdot (Mn, Fe)S$, $(Mn, Fe)S$) as a rule have in time for melting fully for the small time of laser action. Owing to heterogeneity of laser radiation the section of temperature field in action zone is heterogeneity too, see [1], therefore inclusions of one type can to experience different degree of melting in action zone. Dissolution of inclusions in the moment of laser action can not accompany or can accompany with melting. Steel matrix in the contact with inclusions melting or remain hard, that connects with heterogeneity of energy and heat fields [1]. Depth of dissolution zone in inclusion depends on laser treatment regime: more impulse energy W and time of action τ_{imp} more depth of dissolution zone. In the moment of laser action process of dissolution or melting of non-metallic inclusion happens owing to disordered transitions of atoms of inclusion over boundary with molten steel matrix. Mechanism of super-speed dissolution and melting of inclusions connects with mutual mass transfer of atoms (inclusion \leftrightarrow matrix) across interface boundaries which are melted also. Abnormal mass transfer across inclusion-matrix boundaries are accompanied by means of electrons exchange between inclusions (donors) and steel matrix (acceptor), see [2]. Electromagnetic field inducing in the time of laser radiation influence on the conditions of mass transfer. Definite forces action on the components of alloy

under this field and direction of these forces depends on magnetic properties of components of alloy. Action of forces causing with electromagnetic field promotes of mass transfer of components of inclusions and steel matrix which

possess of different magnetic properties (magnetic moments). Thus electron interaction between inclusion and steel matrix is got complicated owing to electromagnetic interaction between atoms of contacting phases.

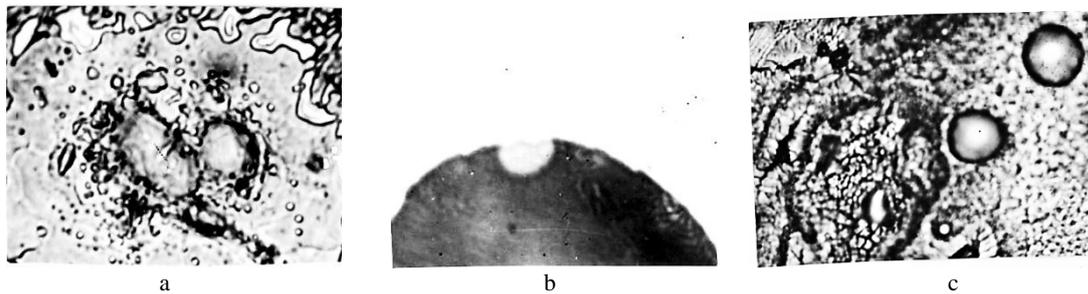


Figure 1. Dissolution and melting of non-metallic inclusions in steel 60G under laser action: a - Al_2O_3 , b - $\text{MnO}\cdot\text{SiO}_2$, c - $\text{MnO}\cdot\text{SiO}_2\text{-MnO}\cdot\text{SiO}_2$; x500x6

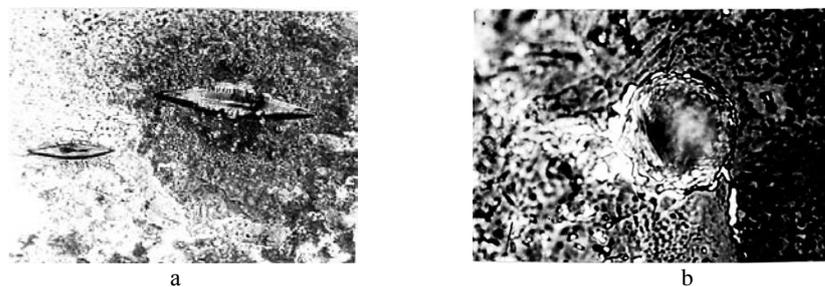


Figure 2. Bands of rapid crystallization in non-metallic inclusions : a - $(\text{Fe,Mn})\text{S}$, steel R7, b - $\text{MnO}\cdot\text{Al}_2\text{O}_3$, steel 08Uy; x500

Mass transfer of components from steel matrix to the surface layer of inclusion can to accelerate the process of dissolution or melting of inclusion if solubility of these elements in inclusion is sufficiently great. Variation of chemical composition on the surface of inclusion and advance of solubility limit of matrix elements realizes the conditions for transition of surface layer of inclusion into liquid state with minimum energy expense on the break of interatomic bonds. Evidently that perhaps connected with distortion of inclusion lattice with the atoms of steel matrix and also with appearing of high-density of crystalline defects and considerable stresses in surface layer of inclusion. Thus in hyper-nonequilibrium conditions of laser action the zone with high-density of vacancies and dislocations in surface layer of inclusion contacting with melted steel matrix is formed. According to dislocation theory of melting, for example, [3], regions of this zone imagining heavy distortion areas with practically disordering lattice perhaps the nucleuses of liquid phase. Atoms with the most breaching electron configurations present in heavy distortion area on the surface of inclusion (nucleus of liquid phase). It is one can to determine critical size of nucleus of liquid phase in surface layer of inclusion. Energy E_{disor} of heavy distortion area of spheroidal shape on the surface of inclusion is determined:

$$E_{\text{disor}} = (4\pi/3) \cdot (1 - V/V_0) \cdot r^3 \cdot Q, \quad (1)$$

where r – radius of nucleus, V/V_0 – an increment in volume of inclusion owing to transition of its areas into

It is possible to imagine the decrease of surface energy owing to contact interaction of inclusion and steel matrix in the moment of inclusion melting is enough considerable in order to system inclusion-interphase boundary-matrix is remained thermodynamically unstable after laser action. Realization of such mechanism of

heavy distortion state, Q – energy which is absorbed owing to transition of inclusion areas into heavy distortion state.

Sequence of heavy distortion areas on the surface of inclusion and also of movement of interphase inclusion-liquid matrix boundary under process of melting one can to present by next image. On the surface of inclusion saturating with elements of steel matrix the heavy distortion areas (areas of melting) are formed. Then they transition into liquid steel matrix completely dissolving in matrix and saturating local areas with the elements of inclusion. Position of inclusion-steel matrix boundary is changed, it is curved in the function of mutual mass transfer. In the moment of the transition of heavy distortion area of inclusion into liquid state the surface area S is changed and energy of interphase inclusion-liquid matrix boundary E_{ipb} is:

$$S = \pi/4 \cdot r^2 \cdot (V/V_0)^{2/3}; \quad E_{\text{ipb}} = 4\pi r^2 \cdot (V/V_0)^{2/3} \cdot \sigma_{\text{h-1}} \quad (2)$$

where $\sigma_{\text{h-1}}$ – stresses on the boundary between hard heavy distortion area of inclusion and liquid steel matrix

Such mechanism of contact melting and dissolution of non-metallic inclusion and inclusion-matrix boundary in molten steel matrix in nonequilibrium conditions is energetically excused since surface layer of inclusion being in stress state with rise energy is substituted for liquid phase with less energy.

melting and dissolution of non-metallic inclusions is determined with value of stresses creating in surface layers of inclusions. Apparently in the conditions of high-speed laser action it is possible practically non-activated transformation of heavy distortion area on the surface of

inclusion into liquid state owing to formation of liquid phase nucleuses under origin of big stresses.

In the conditions of impulse laser action the relaxation processes in surface layer of inclusion do not have a time for development practically therefore time essential for achievement of quasiequilibrium conditions on interphase inclusion-steel matrix boundary is considerably increased. Inner stresses in surface layer of inclusion control the development of melting process which takes place in limited volume owing to preservation of contact between inclusion and steel matrix. Elementary act of stresses relaxation causes simultaneous activation of considerable quantity of the inclusion atoms in disordering process similar of melting. In non-metallic inclusions grain boundaries must to dissolve more quickly than body of grains.

It is possible the realization of mechanism of laser melting (dissolution) of inclusions accounting fact that many of inclusions have nanophase structure [1], with big extent and volume part of grain boundaries. Owing to formation of heavy disordered surface layer in such inclusions in the conditions of mass transfer of liquid steel matrix the melting (dissolution) of grain boundaries takes place probably and nanograins of inclusion with disordered structure depart into molten steel matrix.

Non-metallic inclusion melting or fusing from its surface is been in molten steel matrix and local micrometallurgical bath is formed. In this bath hydrodynamics flows in the conditions of vortex thermo-capillary mixing are appeared that causes movement of inclusion. This carries in the elements of convective mass transfer of components of the inclusion and steel matrix into common process of abnormal high-speed mass transfer. Anisotropy of surface properties of inclusion (or its phases) must to influence on the speed of laser dissolution. Probability of mass transfer from inclusion into steel matrix across interface boundary is more than less of interatomic bonds are broken, or than less of efficiency of space filling of atomic plane. Non-metallic inclusions with powerful anisotropy of surface properties must to have more high speed of dissolution. Process of melting of inclusion is accompanied with high-speed redistribution of forces of interatomic bonds in profit of different types f atoms having favourable relationships of electro-negativities [4]. It is known a big difference of electro-negativity of components causes intensification of bonds between heterogeneous atoms and allows to explain advantage mass transfer of some components from the inclusion into steel matrix or in reverse direction. Stability of non-metallic inclusion under contact interaction with liquid steel matrix depends on the degree of deflection of system from quasi-equilibrium state in the moment of laser action or on the difference of chemical potentials of components in inclusion and steel matrix. Metastable inclusions (or their phases) are more sensitive for contact interaction with liquid steel matrix under laser action. That connects with the free energy. It is more decrease by dissolution of metastable phase than by dissolution of stable phase. Further investigation of thermodynamics performances of components of inclusion and steel matrix and their influence on the character of processes of contact interaction in zone of inclusion-matrix boundary will allows to influence on this interaction under laser action.

After laser quenching from liquid state the areas of laser crystallization in surface layer or in all volume of inclusion are formed. Ultrasmall graininess, columnar shape of grains, zones of shear are characteristics of these areas (see Fig. 2). In the time of laser melting the high degree of nonequilibrium of liquid phase, bifurcation of melt and also transition from laminar to turbulent flow of liquid are

appeared that ensure gradient of oscillation pressure on the inclusion-matrix boundary (liquid if inclusion and steel matrix were melted, or semi-liquid if steel matrix was hard) controlling convective and abnormal flows of mass transfer. Considerable stresses appearing in thin surface layer of inclusion and steel matrix in the result of local heat flashes of laser radiation, see [3], together with action of reactive forces of recoil owing to ejection from the zone of treatment of liquid allows to high-temperature deformation of liquid interlayers continuing under crystallization during cooling. In some non-metallic inclusions being homophase before laser action phase decay in process of nonequilibrium crystallization was happened. That connects with mixing of liquid under action of hydrodynamics forces and temperature gradients. In inclusions disperse particles of second phase or interlayers of different chemical compositions were appeared. The size of these new phases do not depends on energy of impulse practically but it is increased with increase of the time of laser action.

Except homophase non-metallic inclusions of oxides, nitrides, sulphides, silicates there are different heterophase inclusions in steels having various nature and structure [1]. The first one are inclusions "high-melting phase (ph2) surrounding with low-melting cover (ph-c1)" with interphase boundary $ph-c1 \leftrightarrow ph2$. The second one are inclusions "phases ph1, ph2 are beside" with interphase boundary $ph1 \leftrightarrow ph2$. The third one are "eutectics" with interphase boundaries $eu1 \leftrightarrow eu2$. And the fourth one are "dispersed phases (d2) in non-metallic matrix (ph-m1)" with interphase boundaries $ph-m1 \leftrightarrow d2$. Examining the processes of high-speed melting and crystallization of heterophase inclusions under laser action it is necessity to note their common signs and also peculiarities connecting with different structure of these inclusions.

Investigation of high-speed melting and crystallization of heterophase inclusions discovered variety of processes happening in inclusions and steel matrix near inclusions when in the moment of melting micrometallurgical bath is formed and melting of inclusion phases and steel matrix are interacted. Melting of inclusions and both interphase boundaries inclusion-matrix $ph-c1 \leftrightarrow m$ and inside inclusions $ph-c1 \leftrightarrow ph2$ connects with formation of heavy disordered areas on surface of inclusions (nucleus of melting) and abnormal mass transfer as the process of melting of homophase non-metallic inclusions.

Both phases of inclusions "high-melting phase surrounding with low-melting cover" in the moment of laser action are melted but the behavior of their phases is differ with degree of melting. Low-melting sulphide or silicate cover is melted fully, high-melting phase of oxide or nitride is melted partly or fully (Fig. 3, a, b). On the surfaces of both phases mutual saturation was discovered and interphase boundaries inside inclusions are not legible. Low-melting cover of inclusion has interaction with both steel matrix and high-melting phase of inclusion, so it can to dissolve different atoms on the both sides and it can to accelerate process of dissolution or melting if solubility of elements in sulphide or silicate is sufficiently great. On surface of high-melting phase of oxide or nitride saturating with elements of low-melting cover the heavy disordered areas are formed which pass into liquid low-melting phase. Since in the conditions of laser action the relaxation processes in surface layers of both phases of inclusion "high-melting phase surrounding with low-melting cover" are not have time for happen the time for the achievement of quasiequilibrium conditions on both interphase inclusion-matrix boundaries $ph-c1 \leftrightarrow m$ and interphase boundaries inside inclusions $ph-c1 \leftrightarrow ph2$ is increased

considerably. Inner stresses in surface layers of both phases of inclusion control the development of melting process which happens in limited volume owing to preservation of contact between phases of inclusion and also between low-melting cover and steel matrix. Elementary act of stresses relaxation causes activation and drawing in considerable

Both phases of inclusions "phases are beside" in the moment of laser action are fully or partly melted. If the both phases are high-melting they are fused or partly melted (Fig. 3, c, d). Liquid phases are mixed under convective flows in micrometallurgical bath that is accompanied with interaction of components of both phases of inclusion and steel matrix across both interphase inclusion-matrix boundaries $ph1 \leftrightarrow m$ and $ph2 \leftrightarrow m$ and also across interphase boundaries inside inclusions $ph1 \leftrightarrow ph2$. If the both phases are low-melting they are fully melted in the moment of laser action. Liquid phases are mixed and supersaturated liquid solutions are formed then they are

number of atoms of both phases of inclusion to the process of disordered similar melting. After high-speed melting of inclusions "high-melting phase surrounding with low-melting cover" happens the hyper-nonequilibrium crystallization connecting with formation of microphases, nanophases and sometimes of amorphous phases.

crystallized with high speed and zones of liquation are formed too. If the phases of inclusion have very different temperatures of melting they show different behavior in the moment of laser action. Analysis discovered mutual mass transfer between each phase of inclusions and steel matrix and between both phases of inclusions "phases are beside". Change of chemical composition on the surfaces of both phases of inclusions "phases are beside" and achievement limit of solubility of elements creates the conditions in each phase for transition of surface layer to liquid state with minimum expenditures of energy on the break of interatomic bonds.

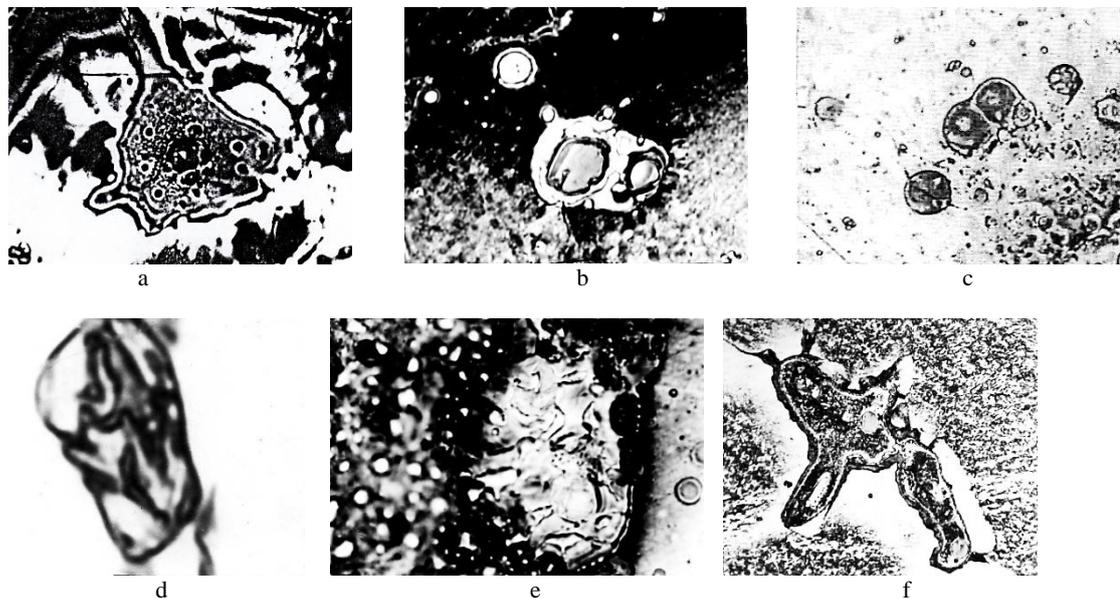


Figure 3. Dissolution and melting of heterophase non-metallic inclusions "high-melting phase surrounding with low-melting cover" (a, b), inclusions "phases are beside" (c, d), inclusions "eutectics" (e, f) under laser action; x500

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. 3, e, f). According to reference [5], abnormal eutectics are formed in conditions when conjugational 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 conjugational 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 $W_{pulse} 10...25$ J were observed. In the resort of $W_{pulse} 30$ J together with abnormal eutectics the sulphide and silicate eutectics inclusions with amorphous structure were observed. Some inclusions have signs of colony structure. 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.

Investigation of inclusions "dispersed phases are in non-metallic matrix" was shown the both phases in the moment of laser action are melted fully or partly. Their behavior is differed from with degree of melting. If both phases $ph-m1$ and $d2$ are high-melting that phase $ph-m1$ is fused or melted in dependence on temperature regime. Dispersed phase $d2$ as a rule have time to melt (or to dissolve) fully in the matrix phase $ph-m1$ of inclusion. Under action of convective flows in micrometallurgical bath the liquid phases of inclusion are mixed though often remnants of phase $d2$ are shown. If both phases of inclusion are low-melting they are melted and mixed. The oversaturated liquid solutions are formed and crystallized with big speed. In such inclusions the zones of liquation are observed connecting with presence of traces of sojourn of former dispersed phase $d2$. If phases of inclusion have different temperatures of melting that low-melting phase $ph-m1$ (sulphide, silicate) is melted in the moment of laser action but high-melting phase $d2$ (oxide, nitride) can to

melt fully or partly. In the time of happens the interaction of components of phase ph-m1 of inclusion with metal matrix of steel promoting the saturation of areas near inclusion with elements of phase ph-m1 of inclusion and also with elements of dispersed phase d2 being in surface area of inclusion. That promotes the rise of level of chemical inhomogeneity of saturated zones in steel matrix in the difference from analogous processes happing under melting of the first and second types of heterophase inclusions. In inclusions after rapid crystallization the heterogeneous distribution of elements is observed connecting with presence of traces of dispersed phase d2 and also with formation of liquation zones revealing with special micro-spectral analysis. In inclusions "dispersed phases are in non-metallic matrix" the zones of laser crystallization with liquation causing owing to the mixing of components of both phases in the moment of melting are formed. In non-metallic matrix of some inclusions the areas with regular distribution of raised and reduced concentration of elements of both phases of inclusion were discovered. Analysis of these areas bears witness about possibility of the rate decomposition of liquid or solid solution. For inclusions "dispersed phases are in non-metallic matrix" after speed crystallization the appearance of ultra small variation in grain size, formation of nano-structure state and also of amorphous and mixed amorphous-nanocrystalline structures are typical. Among inclusions "dispersed phases are in non-metallic matrix" more tendency for amorphization have silicate phases of non-metallic matrix since owing to the interaction of elements of both phases of inclusions in the moment of melting the complicated silicate systems are formed. These silicate systems solidify under speed cooling as amorphous silicate glasses. Moreover inclusions containing phases with B, Ni, Si are subjected to amorphization.

Thus laser action represents method of local change of structure and properties of heterophase non-metallic inclusions.

In the laser strengthening zone of steels we can fix some defects relating to non-metallic inclusions: structural inhomogeneity, brittle cracks and voids, geometrical disruption of strengthening case, sections of oxidation [1]. During laser treatment there are some alterations in non-metallic inclusions and steel matrix. The behavior of non-metallic inclusions in steels under laser treatment depends on their type. High-melting non-metallic inclusions (oxides Al_2O_3 , Cr_2O_3 , SiO_2 , TiO , $\text{MnO}\cdot\text{Al}_2\text{O}_3$, $\text{MgO}\cdot\text{Al}_2\text{O}_3$, $\text{MnO}\cdot\text{Cr}_2\text{O}_3$, TiCN) are melted or remained hard during laser treatment. Low-melting non-metallic inclusions (silicates $\text{MnO}\cdot\text{SiO}_2$, $\text{FeO}\cdot\text{SiO}_2$, sulphides FeS , $\text{FeS}\cdot(\text{Mn,Fe})\text{S}$, $(\text{Mn,Fe})\text{S}$) are melted and spread over a surface under shock wave. The components of inclusions penetrate into steel matrix and saturate it [6]. The motive force of the atoms exchange across interphase boundary is difference of

the chemical potentials of elements containing in the inclusion and steel matrix. Coefficients of diffusion of lattice atoms (of the iron) and of the substitutional atoms near temperatures of steel melting exceed of equilibrium values are of order, coefficients of the interstitial atoms increase some more under laser action [7]. In the conditions of rapid cooling the atoms of elements passing from inclusion to the steel matrix are fixed in solid solution. Zones of steel matrix near inclusions represent solid solution oversaturated with elements of non-metallic inclusions.

Values of microhardness of the steel matrix near non-metallic inclusions and of coefficient K_i depend on the state of inclusion and steel matrix in the moment of laser action. Values of H_{μ}^i and K_i are maximal when all types of inclusions and steel matrix are melted, they are decreased in the cases of melting of steel matrix and hard inclusions and also they are minimal in the cases of hard inclusions and steel matrix. Evidently the state of inclusion and steel matrix determines the degree of saturation of steel matrix with elements of inclusion. Values of K_i are about 1,44...1,86. Special influence of inclusions consists of saturation and oversaturation of local areas of steel matrix with elements of inclusions and of the origin of thermal stresses and also of the localization of relaxation processes having high-speed character.

It is essential to take into account peculiarities of laser treatment: considerable energy of impulse, short-lived time of action, big speed of heating and cooling leading to rapid structural and phase transformations. Laser action is similar to micro-explosion, for example [7]. In shock waves the huge pressures are arisen that leads to plastic relaxation and mass transfer. Under pressure of shock compression the normal stresses exceed yield point. Manifolding of vacancies and dislocations and also dislocation reactions happens. Density of dislocations in zones of laser action is about $10^9 \dots 10^{12} \text{ sm}^{-2}$.

Relaxation of stresses in the zone of laser action is realized owing to plastic shears and rotations and also owing to twinning. The results of these processes are slip lines of a few systems, deformation torchs and "whirlwinds", twins of a few systems, zones of dumping having signs of high-speed deformation. Microplastic processes of relaxation of stresses are localized near non-metallic inclusions (Fig. 4, a). Since in zone of laser action the temperature of steel matrix is risen and also happens the high-speed recrystallization processes having dynamic character and defining with type of steel and its initial state. It is possible polygonization (Fig. 4, b) and also primary (Fig. 4, c), collective and secondary recrystallization accompanying with splitting of grain boundaries and formation of special grain boundaries. Non-metallic inclusions promote nucleation of recrystallized grains.

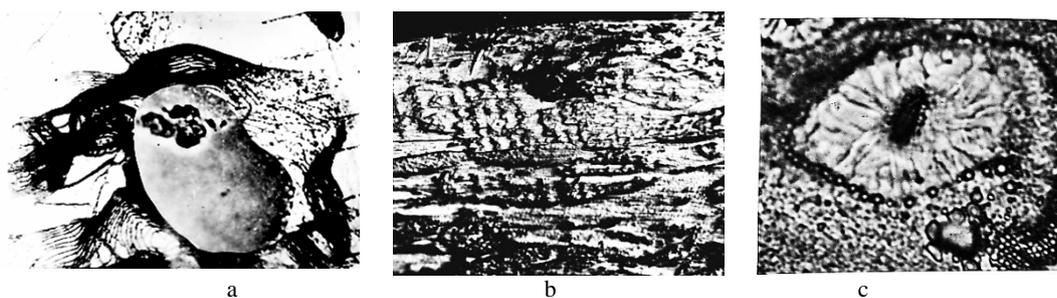


Figure 4. Zones of relaxation of stresses near non-metallic inclusions in low-carbon steels after laser action; x500; c –x1000

Analysis of oversaturated areas of steel matrix near non-metallic inclusions was shown that their structure is heterogeneous. There are a few versions of their structure revealing owing to heat etching under laser action (fig. 5). It may be one zone, or two zones, or three zones; in non-metallic inclusions the surface zone may be absent or may be one zone or two zones. Quantity of oversaturated zones in steel matrix did not depend on the type and state of non-metallic inclusions in the moment of laser action but depends on the regime of laser treatment: when impulse energy was higher and action time was bigger the tendency of multi-layers forming was bigger too. This is caused with activation of mass transfer owing to the rise of energy of laser impulse and increase of possibility of its realization at increase of the action time. Oversaturated areas of steel

matrix near non-metallic inclusions are differed with distribution of chemical elements. At presence of one oversaturated zone near inclusion the gradual decrease of quantity of elements of non-metallic inclusion with removing from the inclusion was observed. At presence of the two or three oversaturated zones in each of them the gradual decrease of quantity of elements of non-metallic inclusion with removing from the inclusion was observed but quantity of elements in the second zone was less than in the first zone and also quantity of elements in the third zone was less than in the first and second zones. Thus at presence of a few oversaturated zones in steel matrix the cascade of elements concentration in zones of interaction between inclusion and steel matrix with gradual decrease of the quantity of elements in each zone were observed [6].

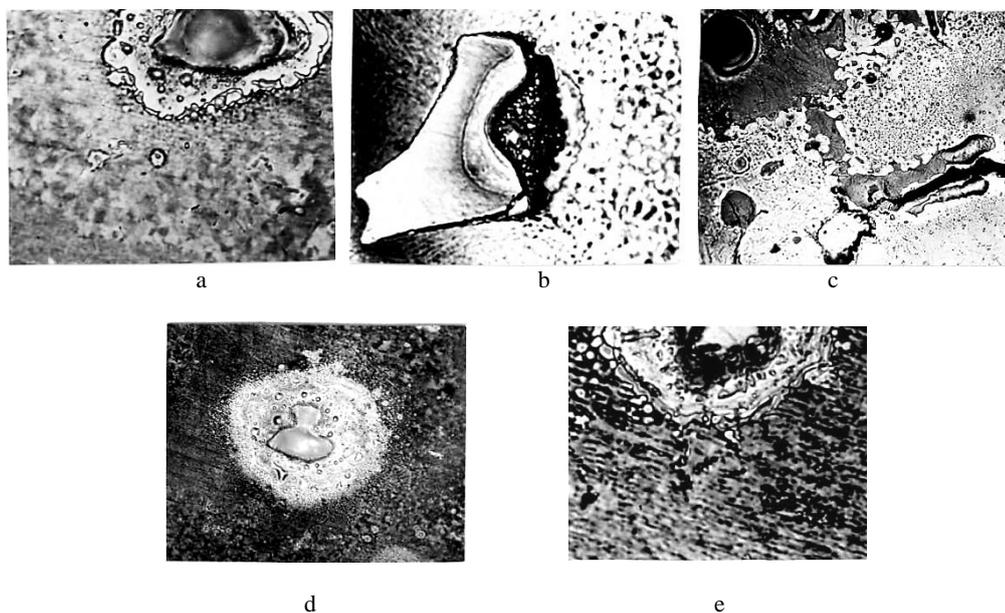


Figure 5. Zones of interaction between non-metallic inclusions and steel matrix under laser action: a, e - SiO₂ steel E3; b, c - FeS-(Fe,Mn)S, steels 08kp and NB-57; d TiCN, steel 08T; - x500x6

Results of distribution of nanohardness of steel matrix were shown that its value (H_n^i) near non-metallic inclusions (one oversaturated zone or first zone) is more bigger than in the distance from non-metallic inclusions (Table 1). Its value depends on the chemical composition and structure of steel defining degree of strengthening under laser action. In the first (or sole) oversaturated zone values of (H_n^i) in 1,45...1,8 time bigger (coefficient K_i) than in steel matrix in the distance from inclusion. In the second and third oversaturated zones values of nanohardness lower than in the first zone but exceeds values of H_n in the distance from non-metallic inclusions accordingly in 1,25...1,64 and 1,1...1,3 time. Thus cascade of nanohardness values with the removal from non-metallic inclusions was observed. Value of nanohardness of steel matrix in all oversaturated zones near non-metallic inclusions and value of coefficient K_i depends on the state of non-metallic inclusion and steel matrix in the moment of laser action. Values of H_n^i and K_i are maximum with the fusion of non-metallic inclusions and steel matrix, they are decreased with the fusion of steel matrix near hard non-metallic inclusion and they are minimum in the cases of

hard condition of non-metallic inclusion and steel matrix. This connects with phenomenon of maximum saturation of liquid steel matrix with the fusion or full melting of non-metallic inclusions [1]. In cases of fusion of oxides, sulphides, silicates in the moment of laser action nanohardness of steel matrix near non-metallic inclusions bigger than near hard non-metallic inclusions and values of coefficient K_i in all oversaturated zones increase. Saturation of steel matrix with elements of non-metallic inclusions and their fixing in the solid solution promotes increase of H_n^i and K_i values. Degree of steel matrix saturation in the second and third zones less than directly near non-metallic inclusions (in the first zone) that is confirmed with difference of H_n^i and K_i values. Dependence of nanohardness of the first (or sole) oversaturated zone of steel matrix near non-metallic inclusions has non-monotonic view for all laser action time (Table 1). This evidence about existence of certain ranges of laser beam energy values that correspond to maximum strengthening of local layers of steel matrix.

Table 1.

Values of nanohardness of steel matrix near non-metallic inclusions (H_n^i) and far from them H_n under impuls energy 25J and action time $3,6 \cdot 10^{-3}$ s

Inclusion, steel	Condition of inclusion in the time of laser action	Condition of steel matrix in the time of laser action	H_n , x 10, МПа	H_n^i , x 10, МПа in zones		
				1	2	3
Al ₂ O ₃ , MgO·Al ₂ O ₃ , R7	fusion	liquid	620	1100	-	-
				1085	942	744
SiO ₂ , R7	hard	liquid hard	620	1080	858	-
				960	-	-
MnO·SiO ₂ 2MnO·SiO ₂ , NB-57	liquid	liquid	748	1130	1050	-
				1260	950	810
TiN, TiCN, 08T	hard, fusion	liquid	280	502	380	-
Al ₂ O ₃ , MnO·Al ₂ O ₃ , 08Yu	hard/ fusion	hard liquid	286	450	385	340
				520	450	-
FeO, FeO·MnO, 08kp	liquid/ fusion	liquid hard	260	460	320	-
				415	-	-
FeS-(Fe,Mn)S, NB-57	liquid	liquid	748	1220	1100	840
				1120	-	-

Main factor of laser strengthening of local areas of steel matrix is its microalloying from inner sources - non-metallic inclusions. Creation of cascade of oversaturated zones near inclusions by formation of local liquational strengthened areas is formation of layers composite near non-metallic inclusions. Structure of these zones maybe single-phase (oversaturated solid solutions) but often dispersal microphases and nanophases – “satellite” particles are observed (see Fig. 4, a, d). Chemical composition of “satellite” particles connects with initial inclusion but slightly differs from it thanks to participation of elements of steel matrix in their formation [3]. For example, near inclusion Al₂O₃ in steel R7 “satellite” particles MnO·Al₂O₃, (Fe,MnO)·Al₂O₃ were observed. Process of “satellite” particles formation is connected with abnormal mass transfer in the moment of inclusions and steel matrix melting then in steel matrix areas enriching by elements of inclusions and also containing of complexes (clusters) of former nano-grains of non-metallic inclusions are formed. Local areas of the type of metallic emulsion smelts are formed. They are “frozen” by abrupt cooling and clusters of former nano-grains of non-metallic inclusions are crystallized into “satellite” particles. And also process of “satellite” particles formation maybe connects with decrease of solubility of elements of non-metallic inclusions in areas of enrichment of liquid or hard steel matrix by abrupt cooling. In the result in steel matrix near initial inclusions composite structure with dispersal particles are formed.

4. Conclusions.

Mechanism of melting of non-metallic 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. And also the peculiarities of formation of the contact interaction zones in steel matrix in the conditions of abnormal mass transfer from inner sources (non-metallic inclusions) under laser treatment were investigated. These zones connecting with origin of the

liquation strengthened areas represent different types of composite layers. Gradiental zones with cascade and “spot” distribution of elements and nanohardness, dispersal zones with different types of strengthened nanophases, “tunnel” zones, and also zones with combine structure were formed. Melting of inclusions under laser action is corresponded with change of their structure and phase composition.

5. Literature.

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