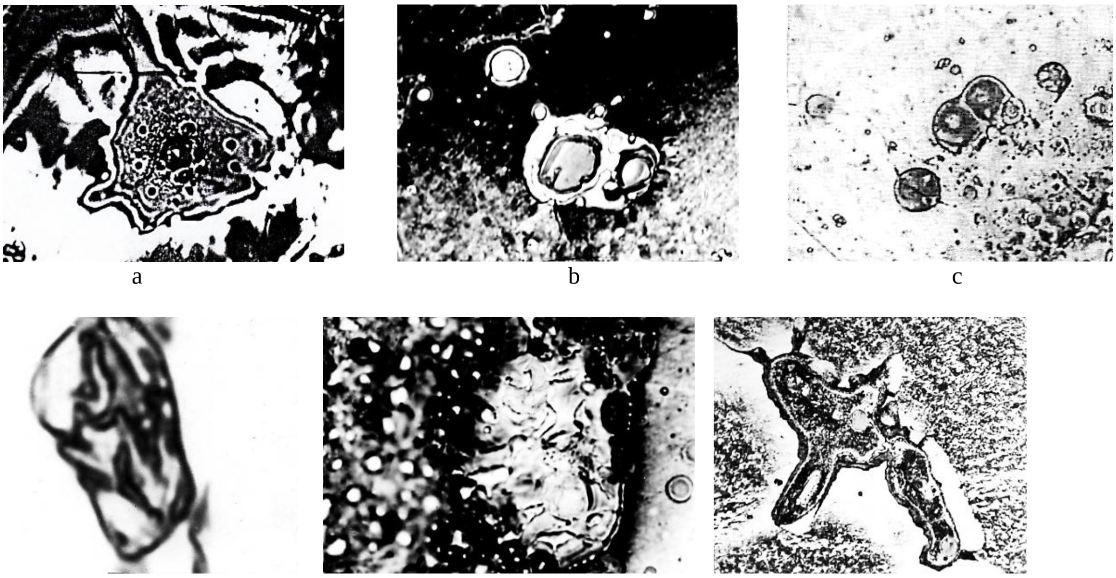
considerably. Inner stresses in surface layers of both phases of inclusion control the development of melting process which happens in limited volume owing to preservation of contact between phases of inclusion and also between low-melting cover and steel matrix. Elementary act of stresses relaxation 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↔m and ph2↔m and also across interphase boundaries inside inclusions ph1↔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.



a b c

d e f

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 0f 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, $MnO^{\cdot}Al_2O_3$, $MgO^{\cdot}Al_2O_3$, $MnO^{\cdot}Cr_2O_3$, TiCN) are melted or remained hard during laser treatment. Low-melting non-metallic inclusions (silicates $MnO^{\cdot}SiO_2$, $FeO^{\cdot}SiO_2$, sulphides FeS, FeS-(Mn,Fe)S, (Mn,Fe)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 $10^9…10^{12}$ 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.

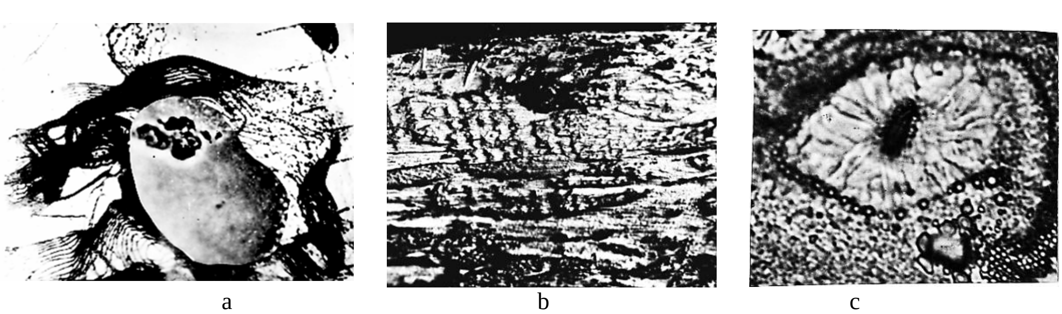

a b c

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 absebt or may be one zone or two zones. Quantity of oversaturated zones in steel matrix did not depends 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 multy-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 then in the first zone and also quantity of elements in the third zone was less then 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].

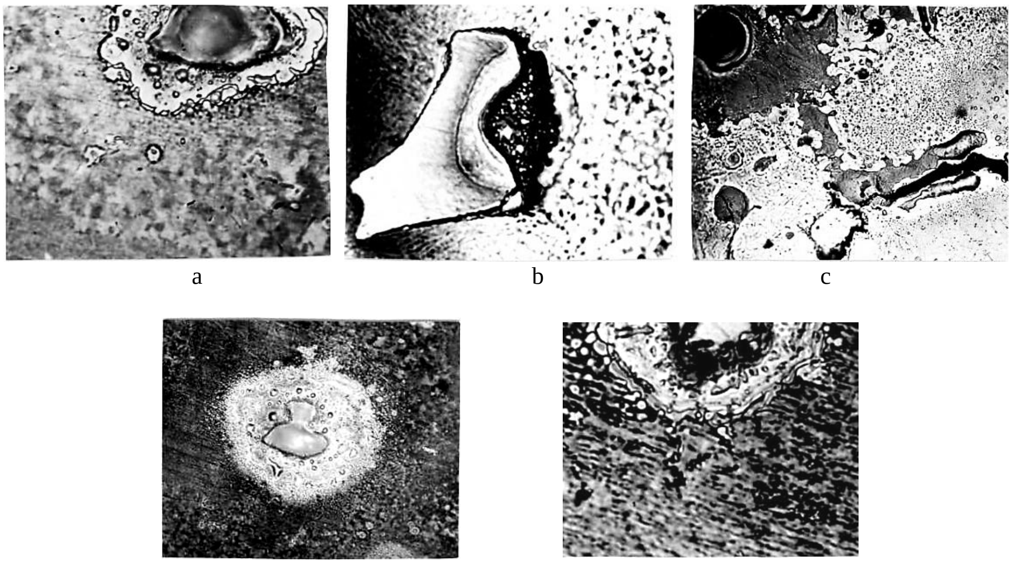


Figure 5. Zones of interaction between non-metallic inclusions and steel matrix under laser action: a, e - SiO_2 steel E3; b, c - FeS-(Fe,Mn)S, steels 08kp and NB-57; d TiCN, steel 08T; - x500x6

Results of distribution of nanohardness of steel matrix were shown that its value (H^i_n) near non-metallic inclusions (one oversaturated zone or first zone) is more bigger then 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^i_n) in 1,45…1,8 time bigger (coefficient K_i) then in steel matrix in the distance from inclusion. In the second and third oversaturated zones values of nanohardness lower then 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^i_n 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 then 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^i_n and K_i values. Degree of steel matrix saturation in the second and third zones less then directly near non-metallic inclusions (in the first zone) that is confirmed with difference of H^i_n 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 strenghtening of local layers of steel matrix.

Table 1.

Values of nanohardness of steel matrix near near non-metallic inclusions (H^i_n) and far from them H_n under impuls energy 25J and action time 3,6· 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^i_n, x 10, МПа in zones		
				1	2	3
Al_2O_3, $MgO·Al_2O_3$,, R7	fusion	liquid	620	1100 1085	- 942	- 744
SiO_2, R7	hard	liquid hard	620	1080 960	858 -	- -
$MnO·SiO_2$ $2MnO·SiO_2$, NB-57	liquid	liquid	748	1130 1260	1050 950	- 810
TiN, TiCN, 08T	hard, fusion	liquid	280	502	380	-
Al_2O_3, $MnO·Al_2O_3$, 08Yu	hard/ fusion	hard liquid	286	450 520	385 450	340 -
FeO, FeO-MnO, 08kp	liquid/ fusion	liquid hard	260	460 415	320 -	- -
FeS-(Fe,Mn)S, NB-57	liquid	liquid	748	1220 1120	1100 -	840 -

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 solusions) 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 Al_2O_3 in steel R7 “satellite” particles $MnO·Al_2O_3$, $(Fe,MnO)·Al_2O_3$ 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-graines of non-metallic inclusions are formed. Local areas of the type of metallic emulsion smelts are formed. They are “freezed” by abrupt cooling and clusters of former nano-graines 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.

1. Губенко С.И. Неметаллические включения в стали. – Днепропетровск: АРТ-ПРЕСС, 2005, 536с. (Губенко С.И., Парусов В.В., Деревянченко И.В.)
2. Самсонов Г.В. Электронная локализация в твердом теле. - Москва: Наука, 1976, 339 с. (Самсонов Г.В., Прядко И.Ф., Прядко Л.Ф.)
3. Найдич Ю.В. Капиллярные явления в процессах роста и плавления кристаллов. - Киев: Наукова думка, 1983, 100 с. (Найдич Ю.В., Перевертайло В.М., Григоренко Н.Ф.)
4. Смиттлз К.Дж. Металлы. - Москва: Металлургия, 1980, 446 с.
5. Таран Ю.Н. Строение эвтектик и создание новых сплавов эвтектического типа. В кн. Сучасне матеріалознавство XXI сторіччя. - Киев:Наукова думка, 1998, с. 176-197
6. Gubenko S. Formation of Gradiental and Composite Zones Near Non-Metallic Inclusions Under Laser Treatment of Steels. - Mechanes, Technologies, Materials 2012, 9th International Congress, Proceedings, Varna, Bulgaria, 2012, v 1: section technologies, p. 19-22
7. Криштал М.А. Структура и свойства сплавов обработанных излучением лазера. – Москва: Металлургия, 1973, 192 с. (Криштал М.А., Жуков А.А., Кокора А.Н.)