

# TRANSFORMATION OF HETEROPHASE NON-METALLIC INCLUSIONS “HIGH-MELTING PHASE SURROUNDING WITH LOW-MELTING COVER” IN STEELS UNDER LASER ACTION

ТРАНСФОРМАЦІЯ ГЕТЕРОФАЗНИХ НЕМЕТАЛЛИЧЕСКИХ ВКЛЮЧЕНИЙ «ТУГОПЛАВКАЯ ФАЗА, ОКРУЖЕННАЯ ЛЕГКОПЛАВКОЙ ОБОЛОЧКОЙ» В СТАЛЯХ ПРИ ЛАЗЕРНОМ ВОЗДЕЙСТВИИ

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**Abstract.** Melting and crystallization of heterophase non-metallic inclusions “high-melting phase surrounding with low-melting cover” was investigated. It was shown that 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 heterophase 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 “high-melting phase surrounding with low-melting cover” and also of the melting of steel matrix play the great role in transformation of interphase inclusion-matrix boundaries under laser action.

**KEYWORDS:** HETEROPHASE NON-METALLIC INCLUSIONS “HIGH-MELTING PHASE SURROUNDING WITH LOW-MELTING COVER”, STEEL, STRENGTHENING, LASER TREATMENT

## 1. Introduction

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  $ph-c1 \leftrightarrow ph2$ . These inclusions influence on the character of strengthening during laser quenching. In the process of laser treatment different phases of these non-metallic inclusions are fully or partly melted down or are remained hard [1, 2]. Distribution of temperature on the surface of specimen influence on the process of interaction between inclusions and steel matrix [3]. In spite of short-term treatment the energy of laser radiation turns out sufficient for melting of the high-melting phase ph-2 and low-melting cover ph-c1, 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, 2]. 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 heterophase non-metallic inclusions and steel matrix, speed transformations which flow in steel matrix. The goal of this investigation was to research the processes of melting, dissolution, crystallization of heterophase non-metallic inclusions “high-melting phase surrounding with low-melting cover” in hyper-nonequilibrium 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 steels R7, 08Yu, 08T, 08Kp, 08Ch18N10T, ShCh15, NB-57, 12GS, E3, 60G were irradiated by laser in GOS-30M installation with an excitation voltage of 2,5kV and pulse energy of 10, 18, 25 and 30 J at heating rate of  $10^5$  °C/s and cooling rate of  $10^6$  °C/s with the action time of (1,0, 2,5, 3,6, 4,2 and 6,0)  $\cdot 10^{-3}$  s. Non-metallic inclusions were identified by metallographic, X-ray micro spectral and petrographic methods [1]. Distribution of elements, microhardness and nanohardness of steel matrix near non-metallic inclusions were determined.

## 3. Results and discussion.

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 micro metallurgical 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.. 1, a, b).

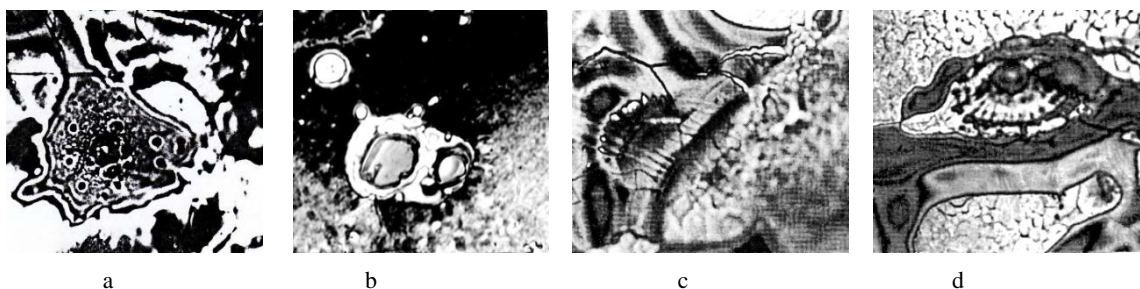


Figure 1. Dissolution and melting of heterophase non-metallic inclusions “high-melting phase surrounding with low-melting cover” under laser action; x500

On the surfaces of both phases mutual saturation was discovered and interphase boundaries inside inclusions are not legible. The interaction between interphase boundaries  $ph-c1 \leftrightarrow m$  and steel matrix is similar to interaction for homophase inclusions. But 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 number of atoms of both phases of inclusion to the process of disordered similar melting.

In the moment of laser melting of inclusions "high-melting phase surrounding with low-melting cover" origin the high degree of nonequilibrium of liquid phases (both phases of inclusion and steel matrix) and bifurcation instability of melt. This ensures gradient of vibration pressure on both interphase boundaries inclusion-matrix  $ph-c1 \leftrightarrow m$  and inside inclusions  $ph-c1 \leftrightarrow ph2$  (fully or partly liquid) which checks convective and abnormal flows of mass transfer. Considerable stresses appearing in thin surface layers of both phases of inclusion and steel matrix in the result of local heat flashes of laser radiation together with action of reactive forces of recoil by ejection from zone of treatment of liquid allows to high-temperature deformation of liquid interlayers continuing under crystallization during rapid cooling.

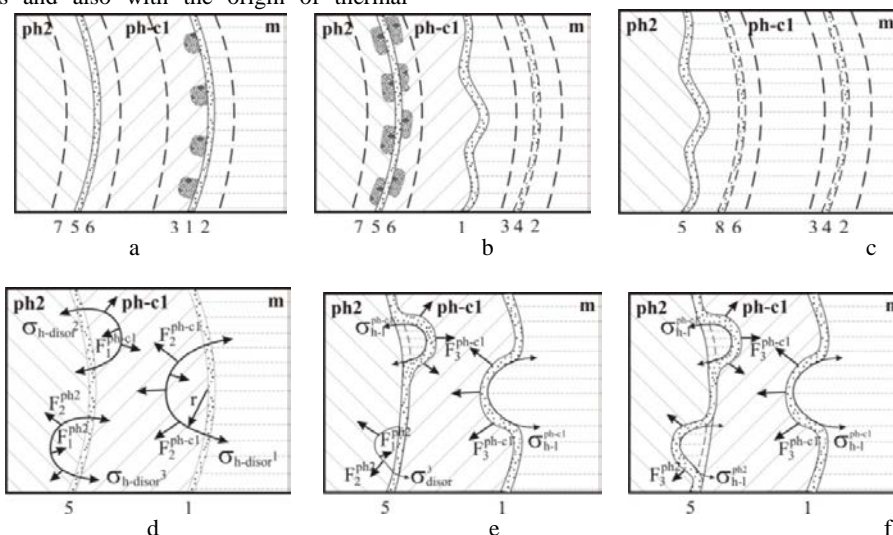
After high-speed melting of inclusions "high-melting phase surrounding with low-melting cover" happens the hyper-nonequilibrium crystallization connecting with formation of microphases, nanophases and sometimes of amorphous phases.

It was shown the formation of gradient and composite zones in steel matrix near non-metallic inclusions take place [1, 2]. Peculiarities of the structure of saturated zones in steel matrix near heterophase non-metallic inclusions depends on their type. All heterophase non-metallic inclusions promote the heterogeneous strengthening of steel matrix. That connects with its microalloying from inner sources – the different phases of non-metallic inclusions and also with the origin of thermal

Amorphous cover forms on the base of silicate or sulphide phase. Evidently silicate compositions have mostly display tendency for amorphization. After laser quenching from liquid state in low-melting cover zone with columnar shape of grains and liquation is formed (Fig. 1, c, d). Sequence of heavy distortion areas on the surfaces of phase-cover  $ph-c1$  and phase  $ph2$  and also of the movement of both interphase boundaries  $ph-c1 \leftrightarrow m$  and  $ph-c1 \leftrightarrow ph2$  under process of melting one can to present with next image (Fig. 2).

On the surface of phase-cover  $ph-c1$  saturating with elements of steel matrix from one side and also saturating with elements of phase  $ph2$  from other side the heavy disordered areas (the areas of melting) are formed (Fig. 2, a, b). Position of both interphase boundaries is changed owing to their melting (Fig. 2, b, c) in dependence on character of mass transfer between both phases of inclusion and phase-cover  $ph-c1$  and steel matrix. Low-melting phase-cover  $ph-c1$  is rapidly melted and it is become the liquid medium in which the high-melting phase  $ph2$  is melted under transition of disordered areas into liquid phase-cover  $ph-c1$ . The phase-cover 1 is saturated with elements of phase  $ph2$ . Process of melting of the inclusions "high-melting phase surrounding with low-melting cover" is corresponded with the change of distribution of forces near heavy disordered areas in the surface layers in both phases of inclusion (fig. 2, d - f). Action of liquid steel matrix causes the change of surface tension of the phase-cover  $ph-c1$  that breaks equilibrium shape of boundary  $ph-c1 \leftrightarrow m$ . Action of liquid phase-cover 1 causes the change of surface tension of the high-melting phase  $ph2$  and that breaks equilibrium shape of the boundary  $ph-c1 \leftrightarrow ph2$ .

Evidently grain boundaries of the both phases of inclusion are melted more quickly than body of grains. That will cause the transition of complexes of former grains (micrograins, nanograins) into liquid state (Fig. 2, g, h). These complexes of phase-cover 1 are become the component of structure of liquid steel matrix and liquid layer on the boundary of phases of inclusion containing both complexes of phase of inclusion has complicated structure. Evidently more complicated processes happen in phase-cover 1 that causes with its contact with steel matrix and phase 2 having different chemical composition and structure. Complicated distribution of stresses in phase-cover 1 causes the moment stresses as in the moment of speed melting and both speed crystallization that causes convective mixing of layers of liquid phase. stresses, big density of crystalline defects and localization of relaxation processes having high-speed character. The interaction between phases of non-metallic inclusions and steel matrix promote the formation of complicated composite zones in the areas of saturating. Such zones consist of microstructural, nanostructural and amorphous elements.



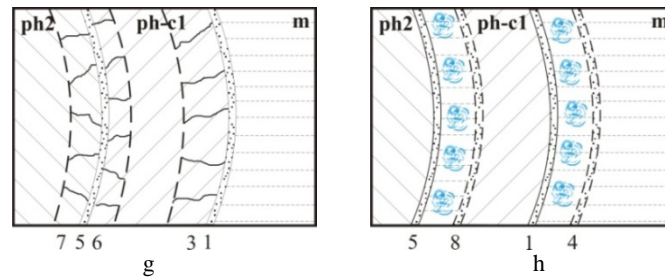


Figure 2. Schemes of laser melting of inclusions “high-melting phase surrounding with low-melting cover”:  $F_1^{ph-c1}$ ,  $F_1^{ph2}$ ,  $F_2^{ph-c1}$ ,  $F_2^{ph2}$ ,  $F_3^{ph-c1}$ ,  $F_3^{ph2}$  – forces of surface tensions on the interphase boundaries,  $\sigma_{h-1}$  – stresses on boundary between hard heavy distortion area of inclusion and liquid steel matrix,  $\sigma_{h-disor}$  – stresses on boundary between disordered area and hard inclusion, 1 – inclusion-matrix boundary, 2 – zone of steel matrix saturation with elements of inclusion, 3 – zone of saturation of phase-cover ph-c1 of inclusion with elements of steel matrix, 4 – initial position of inclusion-matrix boundary, 5 – interphase boundary inside inclusion, 6 – zone of saturation of phase-cover ph-c1 with elements of phase ph2, 7 – zone of saturation of phase ph2 with elements of phase-cover ph-c1, 8 – initial position of interphase boundary inside inclusion

Near inclusions “high-melting phase surrounding with low-melting cover” formation of saturated zones of steel matrix is controlled with the phase-cover ph-c1 which is the source of alloying of steel matrix (Fig. 3). Phase ph2 of inclusion do not takes part in the formation of saturated zones in steel matrix. In the results near these inclusions the composite liquation zones of a few types are formed: the cascade type that bears witness about formation of layers composite zones near such inclusions; “spot” type with heterogeneous distribution of elements of phase-cover ph-c1 and steel matrix; dispersed type that connects with formation of “satellite” particles; complicated layer-dispersed composite with cascade distribution of chemical elements. Characteristic sign of saturated zones is bond of their formation with behavior of the phase-cover ph-c1 in the moment of laser action and with ability of their elements for the speed mass transfer to steel matrix.

Analysis of oversaturated steel matrix areas near non-metallic inclusions “high-melting phase surrounding with low-melting cover” was shown that their structure is heterogeneous. There are a few versions of their structure revealing by heat etching under laser action. It may be one zone, or two zones, or three zones (Fig. 4). By that in non-metallic inclusions surface zone may be absent or may be one zone or two zones.

Results of distribution of nanohardness of steel matrix were shown that its value ( $H_n^i$ ) near non-metallic inclusions

“high-melting phase surrounding with low-melting cover” (one oversaturated zone or first zone) is more bigger than far from non-metallic inclusions (Table 1). Its value depends from chemical composition and structure of steel defining degree of strengthening by laser action. In the first (or sole) oversaturated zone values of ( $H_n^i$ ) in 1,41...1,86 times bigger (coefficient  $K_i$ ) then in steel matrix far from inclusion. These results are closed to results obtaining in [1, 2]. In the second and third oversaturated zones values of nanohardness lower than in the first zone but exceeds values of  $H_n$  far from non-metallic inclusions accordingly in 1,2...1,59 and 1,1...1,35 times. Thus cascade of nanohardness values by removal from non-metallic inclusions “high-melting phase surrounding with low-melting cover” was observed. Value of nanohardness of steel matrix in all oversaturated zones near non-metallic inclusions “high-melting phase surrounding with low-melting cover” and value of coefficient  $K_i$  depends from condition of non-metallic inclusion “high-melting phase surrounding with low-melting cover” and steel matrix in the moment of laser action. Values of  $H_n^i$  and  $K_i$  are maximum by fusion of non-metallic inclusions and steel matrix, they are decreased by 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.

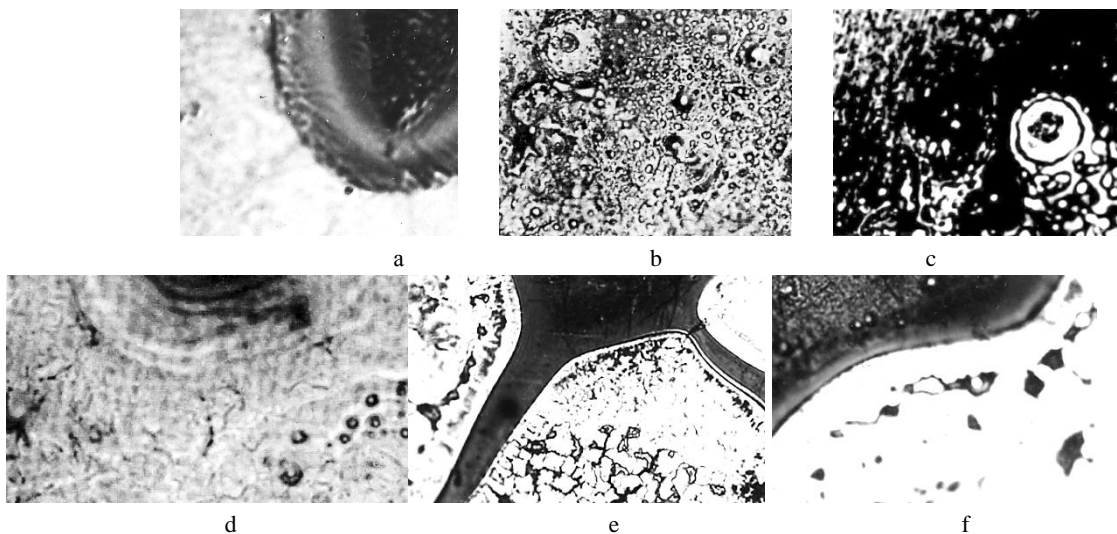


Figure 3. Zones of interaction between heterophase non-metallic inclusions and steel matrix under laser action: a – FeS+MnO·Al<sub>2</sub>O<sub>3</sub>, b – (Fe,Mn)S+Al<sub>2</sub>O<sub>3</sub>, c – MnO·SiO<sub>2</sub>+ MnO·Al<sub>2</sub>O<sub>3</sub>, d – MnO·SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub>, e – MnO·SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub>, f – «satellite» inclusions; x500x6

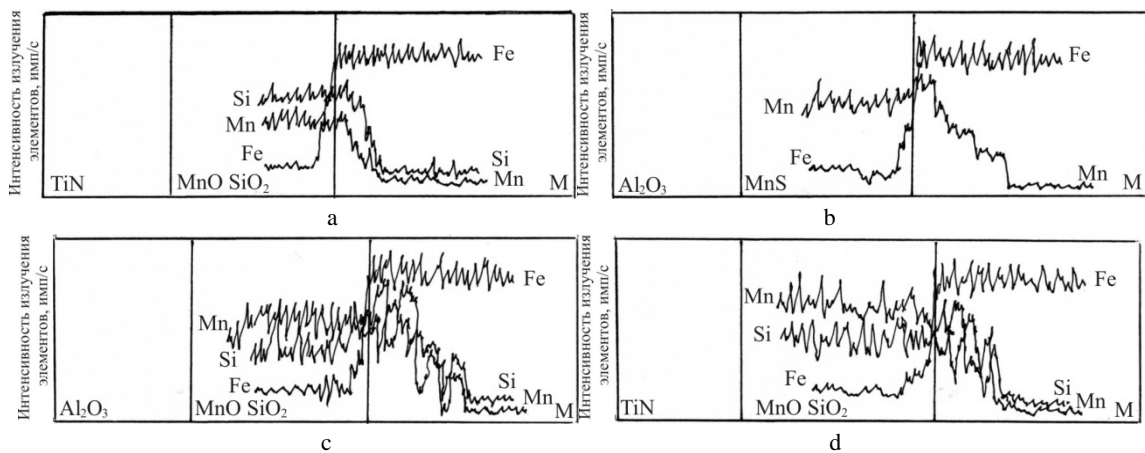


Figure 4. Distribution of chemical elements in inclusions “high-melting phase surrounding with low-melting cover” and oversaturated zones of steel matrix after laser treatment

This connects with phenomenon of maximum saturation of liquid steel matrix by 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 by

elements of non-metallic inclusions and their fix in 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 by difference of  $H_n^i$  and  $K_i$  values.

Table 1.

Values of nanohardness of steel matrix near non-metallic inclusions “high-melting phase surrounding with low-melting cover” ( $H_n^i$ ) and far from them  $H_n$  under impulse energy 25J and action time  $3,6 \cdot 10^{-3}$  s

Inclusion ph-c1 – ph2, steel	Condition of inclusion in the time of laser action	Condition of steel matrix in the time of laser action	$H_n$ , x 10, MPa	$H_n^i$ , x 10, MPa in zones		
				1	2	3
FeS+Al <sub>2</sub> O <sub>3</sub> , (Fe,Mn)S+ MnO·Al <sub>2</sub> O <sub>3</sub> , 08Yu	liquid	liquid	286	531 (1,86)	-	-
MnO·SiO <sub>2</sub> + MnO·Al <sub>2</sub> O <sub>3</sub> , 60G	liquid	liquid hard	620	1054 (1,7)	776 (1,25)	-
MnO·SiO <sub>2</sub> + MnO·Al <sub>2</sub> O <sub>3</sub> , FeO·SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> ,NB-57	liquid	liquid	748	1190 (1,59)	890 (1,19)	-
TiN+TiCN, 08T	hard, fusion	liquid	280	483 (1,73)	-	-
FeO-TiO <sub>2</sub> + TiCN, 08T	fusion	liquid, hard	280	518 (1,85)	361 (1,29)	-
FeO-MnO+ SiO <sub>2</sub> , 08kp	liquid / fusion	liquid hard	260	470 (1,68)	346 (1,24)	-
				423 (1,51)	-	-
				444 (1,7)	335 (1,29)	-
				382 (1,47)	-	-

Dependence of nanohardness of the first (or sole) oversaturated zone of steel matrix near non-metallic inclusions “high-melting phase surrounding with low-melting cover” has non-monotonic view for all laser action time (Table 2). This

evidence about existence of certain ranges of laser beam energy values that correspond to maximum strengthening of local layers of steel matrix.

Table 2.

Influence of laser beam energy on nanohardness of steel matrix near inclusion (Fe,Mn)S+ MnO·Al<sub>2</sub>O<sub>3</sub> in steel 08Uy under different time of action

$\tau_{imp}, \cdot 10^{-3}, s$	$W_{imp}, J$			
	10	18	25	30
1,0	432	495	520	464
3,6	465	520	524	486

Main factor of laser strengthening of local areas of steel matrix is its microalloying from inner sources - non-metallic inclusions "high-melting phase surrounding with low-melting cover". Creation of cascade of oversaturated zones near these 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. 3). 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 [1, 2]. 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 phase ph-c1 of inclusions and also containing of complexes (clusters) of former nano-graines of phase ph-c1 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 phase ph-c1 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 phase

#### 5. Literature.

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ph-c1 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. Appearance of "satellite" particles promotes formation of dispersal composite layers or by presence in steel matrix it promotes formation of zones with combine layers-dispersal structure near non-metallic inclusions "high-melting phase surrounding with low-melting cover". Obviously variation of regime of laser action will allows to regulate structure of these composite systems.

#### 4. Conclusions.

Peculiarities of formation of contact interaction zones in steel matrix in the conditions of abnormal mass transfer from inner sources (non-metallic inclusions "high-melting phase surrounding with low-melting cover") by laser treatment are connected with origin of liquational strengthened zones representing different types of composite layers. Gradiental zones with cascade and "spot" distribution of elements and nanohardness, dispersal zones with different types of strengthening micro- and nanophases, "tunnel" zones, and also zones with combine structure were formed.