BEHAVIOUR OF GRAPHITE IN LASER SURFACE HARDENING OF IRONS

ПОВЕДЕНИЕ ГРАФИТА ПРИ ЛАЗЕРНОМ УПРОЧНЕНИИ ЧУГУНОВ

ПОВЕДЕНИЕ НА ГРАФИТА ПРИ ЛАЗЕРНО ПОВЪРХНОСТНО УЯКЧАВАНЕ НА ЧУГУНИ

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Abstract: *In laser treatment the graphite phase in the gray irons exerts significant influence on the structural changes in the surface layer. Ferrite, ferrite-pearlite and pearlite gray irons with lamellar, nestlike and globular graphite forms have been investigated. The samples were treated by continuous (CO_2) and pulse (Nd:YAG) laser. The graphite inclusions dissolve partially when in solid phase and partially or fully when in liquid phase, as result of the irradiation. Time-energy parameters of the treatment determine the influence on the behavior of the graphite. Different forms of inter-phase interaction were fixed: chemical compounds formation, dissolution, evaporating and sublimation. As a result highly modified and new phases appear, not typical to the phase transformations in the classic heat treatment. Obtaining of nonequilibrium solid solutions and carbides, states closed to amorphous, gas character non-compactness on the surface and in the depth, redistribution of the graphite phase are typical. The graphite quantity decreases because of the carbon saturation of solid solutions, formation of chemical compounds – carbides, nonequilibrium eutectics, graphite evaporating and sublimation as well as obtaining of states closed to amorphous. Compact graphite inclusions interact more difficult than dispersive ones. In presence of compact graphite inclusions explosive evaporating (sublimation) is often observed in graphite rich structural regions, located directly under the treated surface. In high speed treatment amorphous phases could be formatted in regions with limited atom migration and raised contents of C, S and P. They are located mostly on the bottom of the liquid volume in the transition to solid state, highly overheated and then fast cooled micro-volume.*
***KEYWORDS**: LASER TREATMENT, DUCTILE AND GRAY IRONS, GRAPHITE INCLUSIONS*

1. Introduction

Implemented investigations of laser treated Fe-C alloys present considerable effect in improvement of the surface layer properties of gray irons because of their specific chemical composition and structure [1-3]. The main advantage of laser treatment comparing to the other sources of concentrated energy [4, 5] is the possibility for reaching high energy density, especially with pulse lasers [6]. The presence of differentiated graphite phase in the gray irons, characterized with different shape, distribution and graphite quantity, exerts decisive influence on the structure transformation in treatment [7]. The purpose of the present work is to carry out a general analysis of graphite behavior in formation of the structure of the surface layer of irons in treatment by continuous (CO_2) and pulse (Nd:YAG) lasers.

2. Physical basis

The possibility of laser beam for realizing energy treatment with high power on minimum surface (Fig.1) predetermines its universality in wide range of energy density.

Physical phenomena of transformation and reflection of energy from a surface are available on the basis of interaction of laser beam with the surface (Fig.2). The heat resulting of the quantum energy transformation has a practical effect on the treated part. The diagram of the system $Fe\text{-}Fe_3C$ shows the phase equilibrium without giving the presence of a graphite phase really existing in the gray irons (Fig.3). It is characterized with the considerable shift of lines of phase equilibrium depending on the realized cooling rates in crystallization and solid state transformations. It has to be pointed out that the cooling rate after laser heating could reach values up to 10^3-10^{10} K/s. The analysis of the mentioned above is the basis for a next conclusion: in high rates cooling the relative part of the diffusionless transformations increases due to limited mobility of atoms. This could be connected with the presence of large volume of structural states consisting of non-equilibrium solid solutions and chemical compounds. The quantity of so called quasi-eutectic and quasi-eutectoid structural components increases [7] thus giving possibility for obtaining of states closed to amorphous i.e. metallic glasses. Non-equilibrium carbides, different type of martensite, non-equilibrium austenite and ferrite could be observed in the composition of these structures. The behavior of the graphite phase in the gray irons is of special interest because carbon atoms could be dissociated in laser treatment conditions. They could migrate and dissolve in the solid state and liquid environment. In accordance with the existing physic-chemical preconditions evaporating and sublimation could be observed.

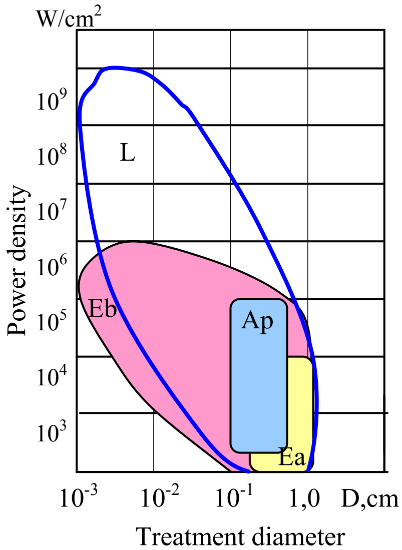

Fig.1 Treatment possibilities of different energy sources: Ap – Arc-plasma, Eb – electron beam, Ea – electric – arc, L – laser.

3. Methodic of the experiments in brief

Ferrite, ferrite-pearlite and pearlite gray irons with lamellar, nestlike and globular graphite forms were investigated. Samples, 20x20 mm^2 in cross section, were treated by continuous (λ=10,6μm) and pulse (λ=1,06μm) lasers. By combining the technological parameters power density - Ns (W/cm^2) and interaction time - τ (s) technological regimes were obtained resulting transformations in liquid or in solid state on the surface layer. Metallographic, durometric and XRD analysis were carried out.

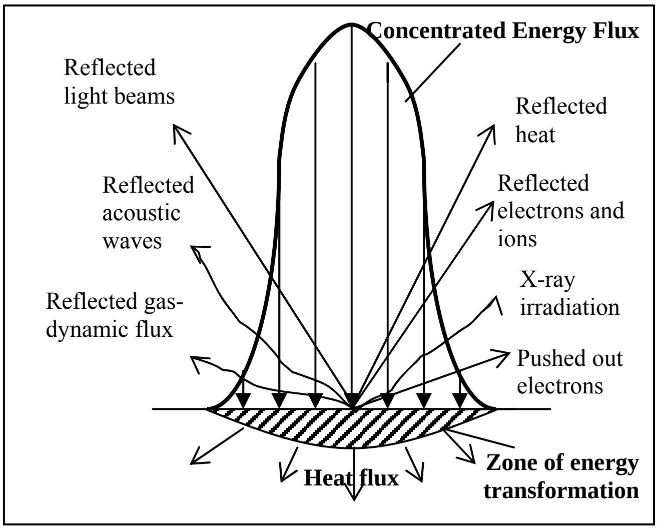

Fig.2 Scheme of the interaction between concentrated energy flux (CEF) and the material.

4. *Results obtained and analysis*

4.1. Graphite behavior according to the classic theory of equilibrium phase transformations

The mechanism of the graphite phase transformations is conditioned by the theory of the phase equilibrium in conditions of slow rate temperature changes. Besides it is considered that the transformations are completed when they reach depletion of non-equilibrium state in the temperature interval given. The transformation mechanism is provoked by the physical-chemical preconditions - temperature, concentration, free energy, which are accepted constant in the particular parts of the macro-volumes. Besides the phase transformations are accomplished from an initial up to the final equilibrium state without typical defects.

The acceptance of considerable importance is that graphite is considered as a stable phase in contrast to the solid solutions and carbides. The only so called "graphitizing" was accepted as possible – graphite dissociating from the other meta-stable states (solid solutions, carbides) and dissolving of the graphite inclusions in the melt. The so called "primary graphitizing" of irons in slow cooling of the melt is also possible.

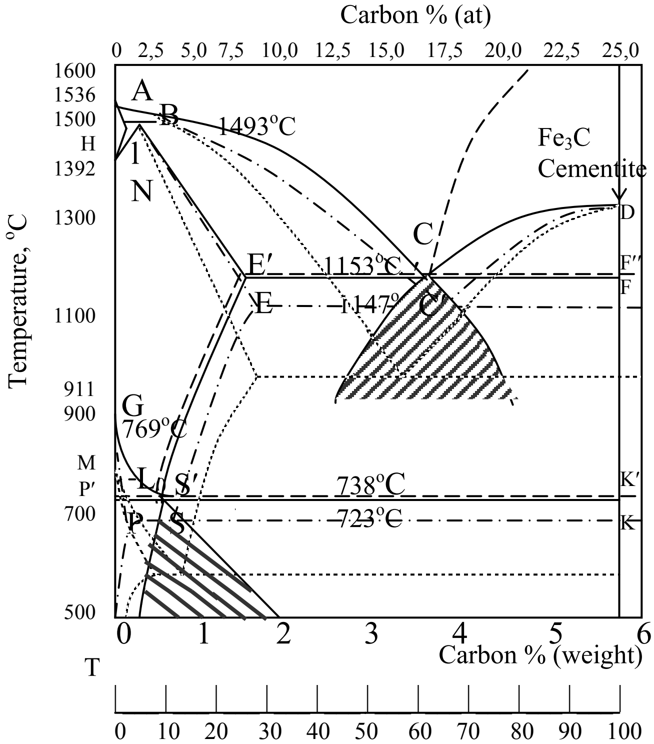

Fig.3 Stable ------ and meta-stable Fe-C state diagrams in different cooling rates:
Classic meta-stable diagram Fe-Fe_3C
In cooling rate V_1
In cooling rate V_2, $V_2 > V_1$.

4.2. Graphite behavior in conditions of non-equilibrium heating and cooling

The kinetics of the physical-chemical processes in the surface layer in laser treatment allows the morphology of the phase transformations to be discussed in the following main aspects: high and ultrahigh heating and cooling rates, mechanisms of atom migrations different from diffusion, considerable heterogeneity of phase transformations in space and time. Processes quite different from these well known in the theory of equilibrium phase transformations were observed: partial dissolving of the graphite phase in the melt, partial or complete evaporating and sublimation of the graphite inclusions, migration of the carbon from the graphite phase to the adjacent solid phases in heating (Fig.4). As a result of

*Fig.4 Non-compactness in the bottom of the melted pool due to the partial evaporating of the graphite inclusion. (SCh15, N_s=1.9*10^4 w/cm^2, E_v=1.58*10^4 J/cm^3).*

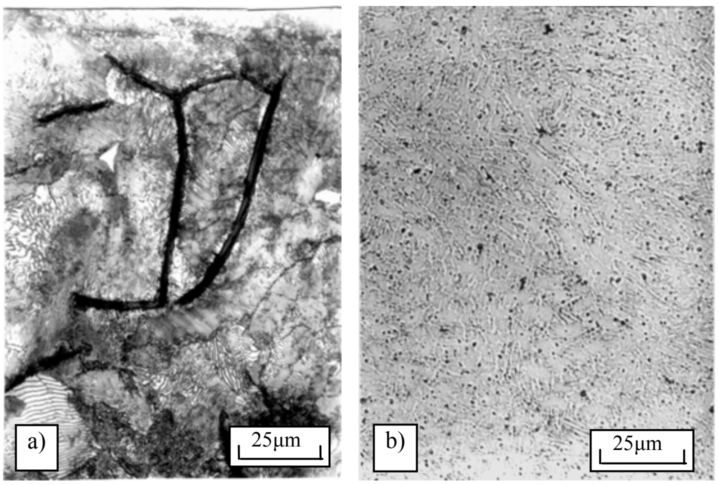

*Fig. 5 Microstructure of the basic iron SCh30 – a) and of the laser melted surface layer – b) (N_s=2.5*10^4 w/cm^2, v=1.2 cm/s, E_v=2.08*10^4 J/cm^3).*

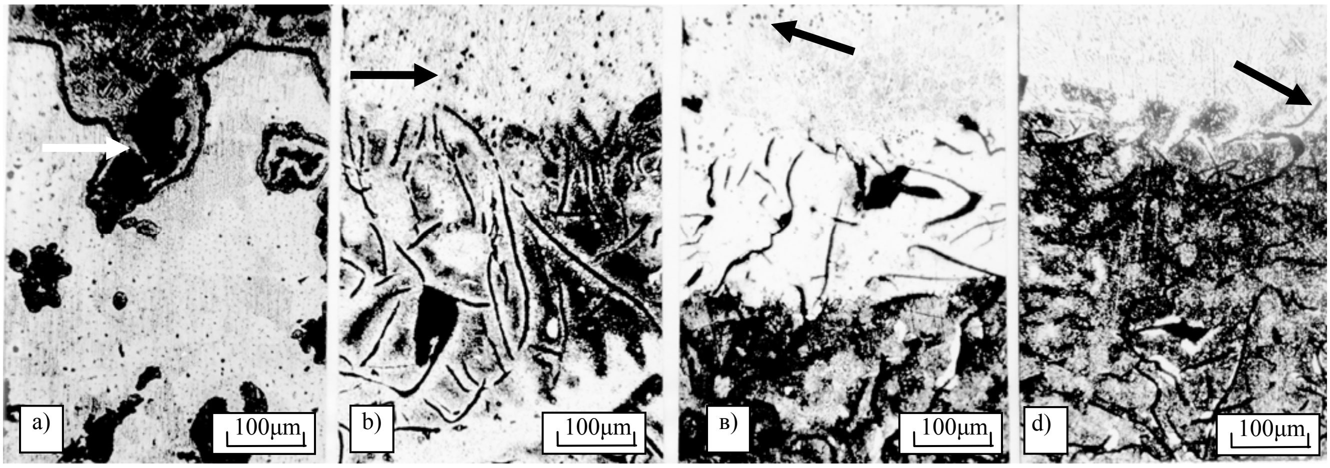

*Fig.6 Different degree of graphite dissolving in the melt. a) Ferrite ductile iron, pulse laser, N_s=2.2*10^6 w/cm^2, τ=10^{-2}s; b) Pearlite – Ferrite (2.0%F) gray iron, continuous laser, N_s=1.8*10^4 w/cm^2, τ=0.8s; c) Pearlite gray iron (F<2%), continuous laser, N_s=1.8*10^4 w/cm^2, τ=1.6s; d) Pearlite gray iron (F<2%), continuous laser, N_s=1.8*10^4 w/cm^2, τ=0.8s;*

these processes changes in the number of phases and their quantitative correlation were observed in the following cooling. After crystallization considerable homogeneity was observed in the cooled liquid phase (Fig.5). The typical characteristic of the carbon migration is the direction, which is opposite to that of the heat flux. This migration, called by us "thermo-kinetic" is accompanied by an effect of migration under pressure. Because of the many times smaller graphite heat capacity the inclusion is heated up to considerably higher temperature and its aspiration for extension leads to pressure being increased. It is the reason for forcing the carbon atoms out to the adjacent phases. Practically unlimited possibilities for carbon migration from the graphite to the liquid phase often lead to its complete dissolution, intensified by the thermo-kinetic stirring of the melt.

As a result of carbon migration from graphite to the adjacent low-carbon phases regions with new formed carbide, called "synthesized" could be seen (Fig.6). The location around the graphite inclusions is its typical characteristic. In our opinion this is not probably the equilibrium carbide Fe_3C. The formation of the non-equilibrium carbides type M_2C, $M_{23}C_6$, M_7C_3, M_6C and MC is also possible.

The dissolution degree of the graphite in the melt depends on its form, distribution, sizes and the quantity in the graphite phase. When the power density increases and the interaction time decreases considerable part of graphite remains. When increasing interaction time and remain relatively high power density the result is explosive evaporating and sublimation is the. It leads to appearance of craters on the surface which is unallowable technological defect. Non-compactness appears also in depth when the gas phase could not leave the melt (Fig.7).

4.3. Formation of structural states closed to amorphous

In the investigations carried out structural zones were located close to the graphite inclusions, slightly etched by metallographic reagents were observed (Fig.8). We suppose that these are "metallic glasses" locations in the micro-volumes. The following peculiarities are specific for these regions: irregularity concerning to their location around the graphite – they are larger in the direction of the liquid volume. They are located above the structures consisting of martensite and austenite resulting of phase transformations in solid state. The micro-hardness of these regions is in the range 1150-1250 HV 0,1.

5. Conclusion

On the basis of the investigations carried out and their analysis the following conclusions could be made:

- In laser surface treatment the graphite phase considerably influences the kinetics and the morphology of phase transformations in gray irons;
- In solid state transformations carbon migration from graphite inclusions is observed. It leads to changes of phase quantity and their correlation including carbide synthesis;
- The carbon of the graphite dissolves most completely in the

*Fig. 7 Gas inclusions and craters due to the graphite evaporating (SCh20, N_s=2.5*10^{5}w/cm^2, τ=4*10^{-2}s).*

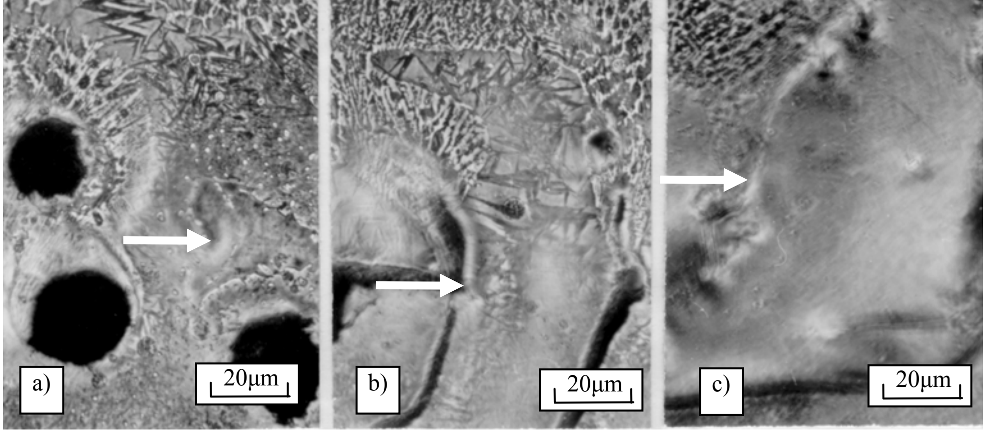

*Fig.8 Zone with structure closed to the amorphous. a) Ferrite – pearlite ductile iron, N_s=2.1*10^4 w/cm^2, τ=4*10^{-1}s; b) Ferrite – pearlite gray iron (5%F), N_s=9.8*10^{4}w/cm^2, τ=9.3*10^{-2}s; c) Ferrite – pearlite gray iron (20%F), N_s=8.6*10^5 w/cm^2, τ=4.6*10^{-2}s*

liquid state resulting on the surface layer. The fine lamellar graphite forms dissolve most easily and most rapidly comparing to the nestlike and globular ones;

- Graphite evaporating and sublimation are possible resulting appearance of non-compactness in depth and craters on the surface layer;
- Micro-regions with structure closed to amorphous, located around the graphite inclusions, were observed.

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