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SURFACE TOPOLOGY OF Fe-Si ALLOY IN THE LASER RADIATION EXPOSURE

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Abstract. It is shown that when a metal surface is exposed to laser radiation, a wavy-like relief is formed on it. According to the data obtained, three stages of spatial growth of the waves can be noted: area of surface stabilization, area of exponential and nonlinear wave growth. Formation of the wavy-like relief of a crater is connected with the appearance of thermocapillary instability. Wave breaking in the stage of nonlinear growth could be related to the difference of phase velocities.

1. Introduction

The appearance of lasers has provoked an intense development of research in the field of impulse energy actions. Due to the special properties of laser light (coherence, polarization, high energy density, etc.) it has become possible to manage internal processes in a solid state, and to produce surface modification of materials [1, 2], particularly in metals.

2. Experimental technique

Polycrystalline Fe-Si alloy plates (Si ~ 3.4 %) of 0.25 mm thick and with an average particle size of 10 mm, made as metallographic grinding, were used in the experiments. The samples were treated by the laser facility LTA-4-1 using yttrium-aluminum-garnet-based elements (λ = 1.064 mm). Topological research of the surface after laser radiation was performed on a metallographic microscope, as well as on the non-contact profilometer Wyko NT 9080 (Bruker AXS) (wavelength $\lambda \sim 670$ nm).

3. Experimental results

Critical density of radiant energy has been determined, the excess of which leads to melting of the surface $\approx 1.07 \cdot 10^5$ W·cm^{-2} for a rectangular pulse with a duration of 3 10^{-3} s. The results are presented in Fig. 1. It is seen that when the surface is irradiated at the rate of $1.07 \cdot 10^5$ W·cm^{-2} (Fig. 1a), it is melted that is characterized by the formation of a single wave. In the area of fusion, after exposure to laser radiation at the rate of ~ $1.1 \cdot 10^5$ W·cm^{-2} (Fig. 1b), a quasi-periodic wave relief starts forming on the surface of the Fe-Si alloy. This rate is the threshold for the formation of a relief wave.

The melt height above the equilibrium surface at low rates does not exceed 3-4 microns (Fig. 1 a-c), whereas irradiation of the Fe-Si alloy surface at a high rate rises the melt up to 8 microns (Fig. 1 d-g). This is accompanied by a change in the total curvature of the surface. At low power density of laser (Fig. 1 a-c), the wave relief is formed on a flat surface. As the rate is increased, a considerable curvature of the surface appears (Fig. 1 d-g), which indicates the formation of the molten pool and the existence of surface convective streams in the melt. Because of this, the surface in the area of exposure to radiation takes a toroidal-like shape, on which a wavy relief is formed (Fig. 1 d-g).

On the basis of the investigation of the melt surface at the time of laser radiation [3-5], it can be concluded that the disturbance appearing on the surface of the melt is carried away from the center to the periphery. Therefore, applying the above proposition to this case, the formation of the relief is associated with convective instability of the surface capillary wave propagation.

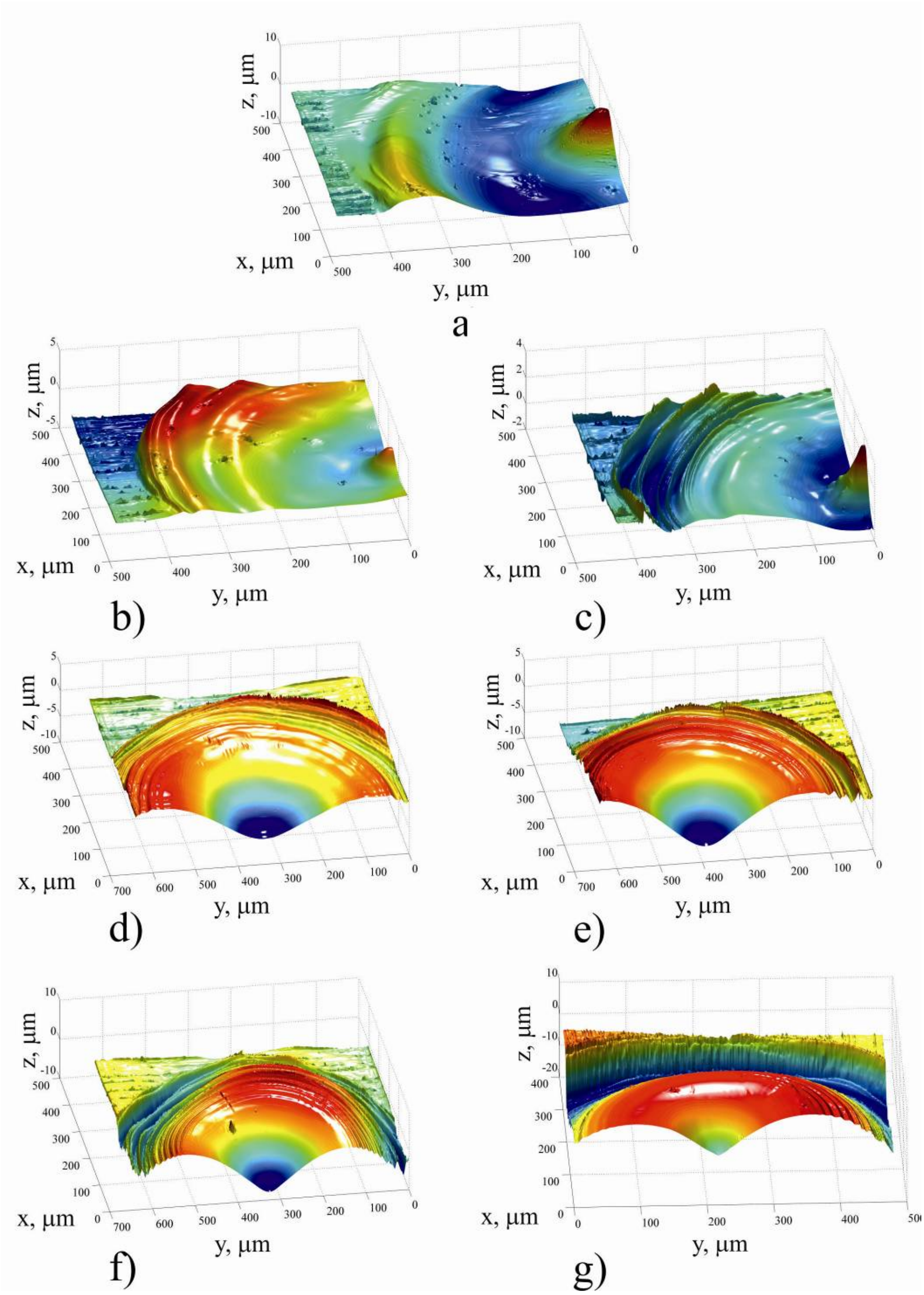


Fig. 1. Evolution of crater topology at different power densities of a laser:
a) $1.07 \cdot 10^5$ W·cm^{-2}; b) $1.10 \cdot 10^5$ W·cm^{-2}; c) $1.16 \cdot 10^5$ W·cm^{-2}; d) $1.3 \cdot 10^5$ W·cm^{-2}; e) $1.53 \cdot 10^5$ W·cm^{-2}; f) $1.7 \cdot 10^5$ W·cm^{-2}; g) $2.21 \cdot 10^5$ W·cm^{-2}.

Thus, the relief of a crater formed by the impact of laser radiation is the result of the movement of capillary waves on the surface of the melt, which provides information about the evolution of capillary waves in space. For this purpose, it is advisable to study crater profilograms.

Figure 2 shows a profilogram featuring the peculiarities of forming the wave relief. A crater produced by irradiation at the rate of $2.21 \cdot 10^5$ W·cm^{-2} was chosen as a typical example of the wave relief. The inset shows dependence of the change of the wave amplitude (the difference between neighboring amplitudes) on the distance from the center of a crater.

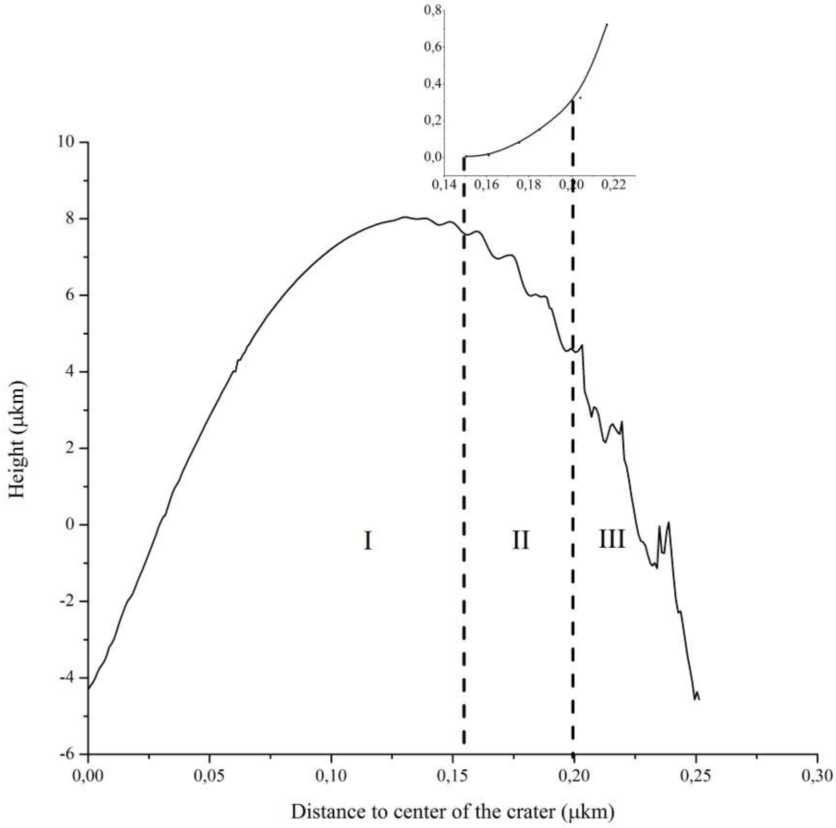


Fig. 2. Dependence of the melt height on the distance to the crater center for $2.21 \cdot 10^5$ W·cm^{-2}.

According to Fig. 2, the formation of the relief in the crater has three distinct areas:
1) area of surface stabilization (~ 0.15 mm), wave formation does not occur;
2) area of exponential growth of waves (~ 0.05 mm), in the inset, dependence of the amplitude on the distance to the center of the crater;
3) Area of non-linear growth of waves (~ 0.05 mm).

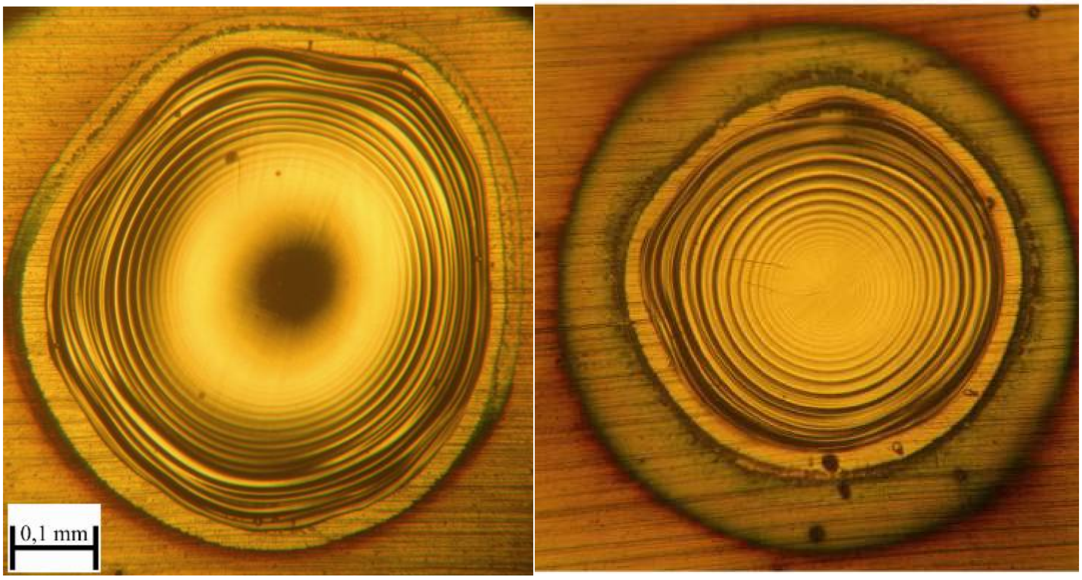
The existence of these areas characterizes the surface of the melt as a non-linear medium-amplifier.

In the area of non-linear growth of waves, there is a division of the wave into two separate ones. This may be due to the emergence of secondary instabilities when the amplitude of the initial wave exceeds the critical value [6], which is due to the difference in their phase velocities. The critical amplitude of the wave for the front side is 0.6 m.

The increase of power density of laser up to ~ $2.64 \cdot 10^5$ W·cm^{-2} leads to forming areas on the opposite side of plates ~0.3 mm thick similar to the impact area on the front side (Fig. 3a, b). On the reverse side, as can be seen in Fig. 3b, there is a more visible relief. Figure 4 shows a detailed typical topology of an output crater on the other side when a metal surface is exposed to radiation at the power density rate of $2.9 \cdot 10^5$ W·cm^{-2}.

As Fig. 4 shows, the melt performs volume oscillations with amplitude of over

10 microns. The relief profile of the crater is shown in Fig. 5. One can see the formation of three areas, with the area of non-linear growth being ~ 0.075 mm wide.



a) b)

Fig. 3. View of a typical fracture of iron surface when exposed to laser radiation at the rate of $2.9{\cdot}10^5$ W·cm^{-2}; a) front side, b) bottom side.

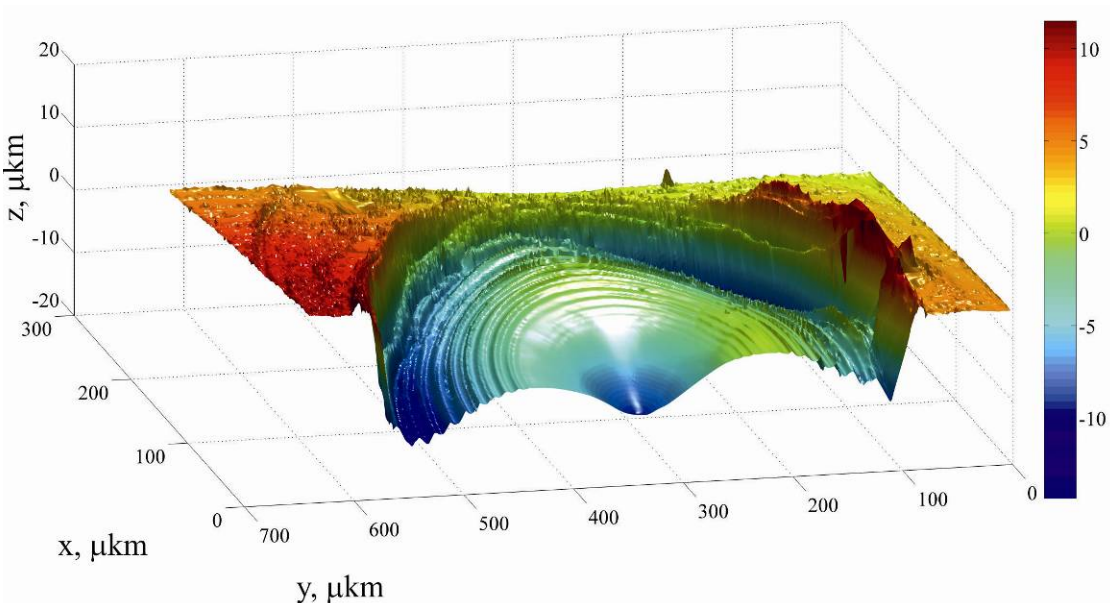


Fig. 4. Typical topology of a crater on the bottom side of a plate, resulting from exposure to laser radiation of $2.9{\cdot}10^5$ W·cm^{-2}.

4. Discussion of results

The shape of the central part of the crater (Fig. 4) shows the appearance of a cavity (hollow channel) during the exposure to laser radiation. Partial collapse of the cavity leads to a depression in the center of the crater.

It is known [7, 8] that thermocapillary instability is accompanied by the formation of an annular periodic texture on the surface of metals with a typical period of about 10^5-10^4 m^{-1}.

To compare the tested structures with this mechanism, wave numbers of the wave-like relief were calculated. The wave numbers of the wave-like structures for the front and the back were respectively as follows: for the front side $k_1 = 5.2\ 10^5\ m^{-1}$; for the back side $k_2 = 10^6\ m^{-1}$.

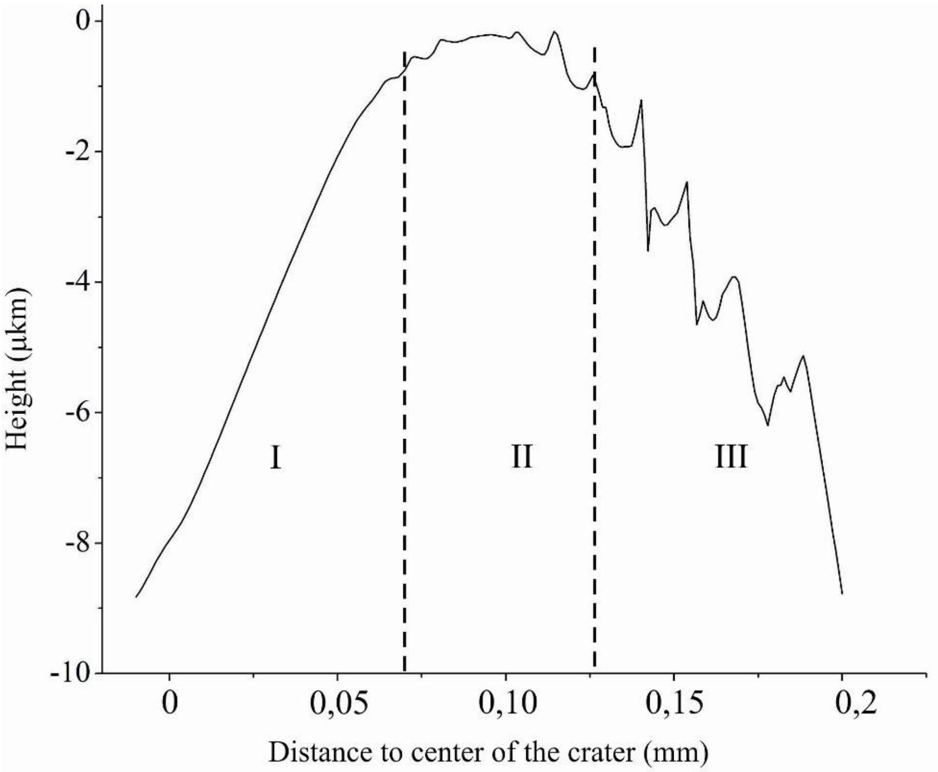


Fig. 5. Profilogram of the crater on the bottom side of a plate.

These values are of the same order as the structures formed by the thermocapillary mechanism. Sufficient conditions for thermocapillary instability are as follows: formation of a melt on the sample surface (which occurs at about $1 \cdot 10^5$ W·cm^{-2}); a significant radial temperature gradient in the molten pool (~ 10^6 K m^{-1}); a thermal flow directed along the normal to the surface of the melt (e.g., resulting from a thermal radiation). The time increment of thermocapillary instability is ~ 10^3 s^{-1} for the wave numbers of ~ 10^5 m^{-1} [7], which is comparable with the time of laser radiation effect and typical parameters of created structures.

5. Conclusion

The topography of a crater undergoes significant changes when the power density increases. Three areas of wave growth have been discovered, which describes the surface of the melt as a non-linear medium-amplifier [6]. It has been shown that the formation of undulating topography of the crater is caused by thermocapillary instability.

Acknowledgement

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