THE ACTION OF INTENSE LIGHT BEAMS ON METAL SURFACES

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Studies of the effect of lasers on metals have shown that the action of intense light beams leads to the formation of craters on metal surfaces. A considerable increase in hardness is often observed in the region of such craters; the hardness of low-carbon steels may reach 700 kg/mm^2, which is considerably higher than that produced by other heat and mechanical treatments.

An important place among modern methods of strengthening of metals is occupied by impulsive interaction techniques. According to data due to Rinehart and Pearson [1], for instance, the hardness of low-carbon steel specimens hitting a steel plate with a velocity of about 400 m/sec may be increased by 130 kg/mm^2. Increasing the impact velocity to 3000 m/sec produces no further increase in hardness. A somewhat larger increase in hardness (about 220 kg/mm^2) can be attained by increasing the impact velocity to about 4000 m/sec, and hence reducing considerably the interaction time. It should be pointed out, however, that starting from a certain critical impact velocity, weakening rather than hardening of the metal surface takes place. A well known and extensively studied hardening method is quenching of metals and alloys. The aim of the present investigation was to explore the possibilities of hardening of metals by very short energy pulses.

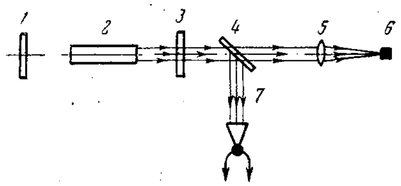

Fig. 1. Principal optical system of the laser used in the experiments: 1) mirror with reflection coefficient R = 99%; 2) ruby crystal (source of monochromatic radiation); 3) mirror with reflection coefficient R = 30%; 4) plane-parallel glass plate; 5) lens; 6) irradiated specimen; 7) thermocouple calorimeter.

A laser was used as the source of pulsed energy. A diagram of the apparatus used is shown in Fig. 1. Monochromatic light from a ruby crystal (wavelength $\lambda = 6943$ Å) was focused by a lens on a metal specimen surface. The normal mode of laser operation, i.e., without modulation of the resonator Q, was used; this mode is characterized by multi-spike generation which in the apparatus used lasted approximately 500 microseconds. The number of pulses per shot was 60–80, each pulse lasting 2–3 microseconds. An oscillogram of the laser radiation is shown in Fig. 2, where the time marks represent 100 microsecond intervals. The total radiation energy per shot, measured with a thermocouple calorimeter (shown schematically in Fig. 1), was 1.4–1.6 joule. Two type IFP-2000 lamps were used to "pump" the ruby crystal.

The effect of laser radiation was studied on armco iron, a low-carbon steel 10 (0.1% C), high-carbon and high-alloy steels, tin and duralumin. It was found that a light beam (with above characteristics) normal to the metal surface produces a crater about 1.5 mm in diameter and 1.5 mm deep. Metallographic examination showed that three zones can be distinguished in craters formed in steel. Zone 1 nearest to the crater surface has a fine acicular structure which obviously consists of martensite needles. The next zone 2 contains white etch-resistant regions which consist of grains of complex shape; zone 3 has the original structure. A photomicrograph of a crater in steel 10 is reproduced (at low magnification) in Fig. 3 showing all the three zones. For the sake of convenience, this photograph shows not the initial specimen surface, but the surface after the removal of a thin surface layer, as a result of which the crater diameter was reduced to 1.0 mm.

Microhardness measurements showed that, in the case of steel 10, the initial structure (zone 3) consists of ferritic grains with a hardness of 200 ± 40 kg/mm^2 and pearlite grains with a hardness of 300 ± 40 kg/mm^2, After laser irradiation the hardness of zone 1 is 1000 ± ± 400 kg/mm^2. Consequently, in spite of the apparent uniformity of zone 1, its properties vary within wide limits and its hardness is very high. The second zone consists of white etch-resistant grains, whose hardness is 1000 ± 500 kg/mm^2. In spite of similar hardness, the structure of the white grains in zone 2 and the structure of zone 1 are not the same, since no martensite needles present in zone 1 are ever revealed by the same etchant in zone 2. In addition to white etch-resistant grains, zone 2 contains regions which resemble ferrite grains in zone 3; the hardness of these grains, however, is 270 ± 40 kg/mm^2, against 200 ± ± 40 kg/mm^2 recorded for the starting material. A photomicrograph of these regions at high magnification is reproduced in Fig. 4.

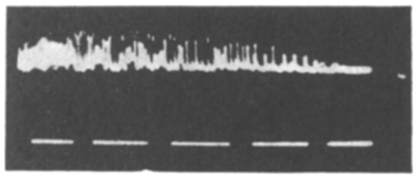

Fig. 2. Oscillogram of ruby laser radiation; the time marks represent 100 microseconds.

The periphery of a crater on the surface of steel 10 is shown at magnification × 450 in Fig. 5 and reveals a clearly defined boundary between the initial structure (zone 3), consisting of white ferrite and black pearlite grains, and zone 2, in which the color of the initial pearlite grains is changed as a result of a transformation under the influence of laser radiation. A similar boundary separates zone 2 from zone 1, which is adjacent to the crater and which has a finely acicular structure.

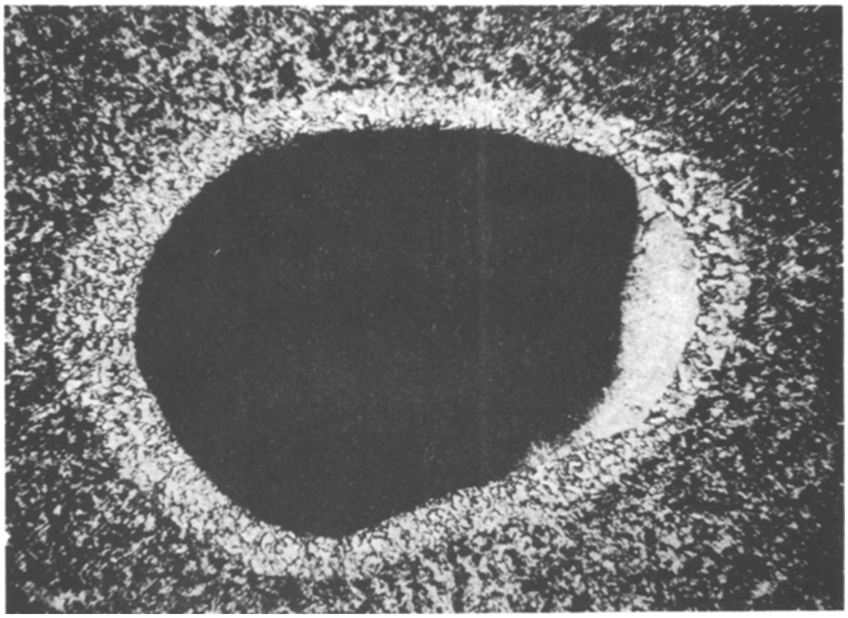

Fig. 3. Microstructure of the surface of steel 10 subjected to laser radiation; zones 1, 2 and 3 are clearly visible (×70).

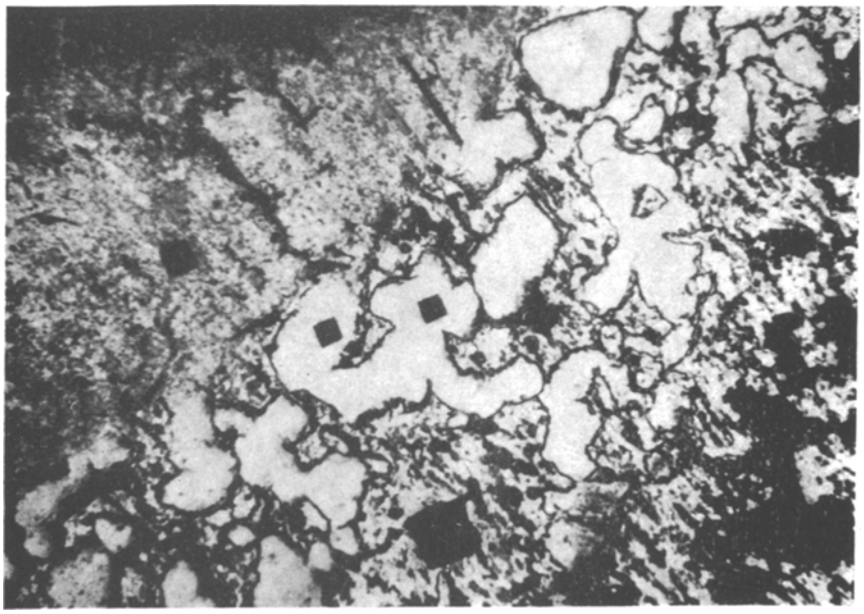

Fig. 4. Region of a crater on a steel 10 surface, showing zones 1, 2 and 3 with indentations made by the diamond pyramid identer of a microhardness tester under a load of 50 g (×450).

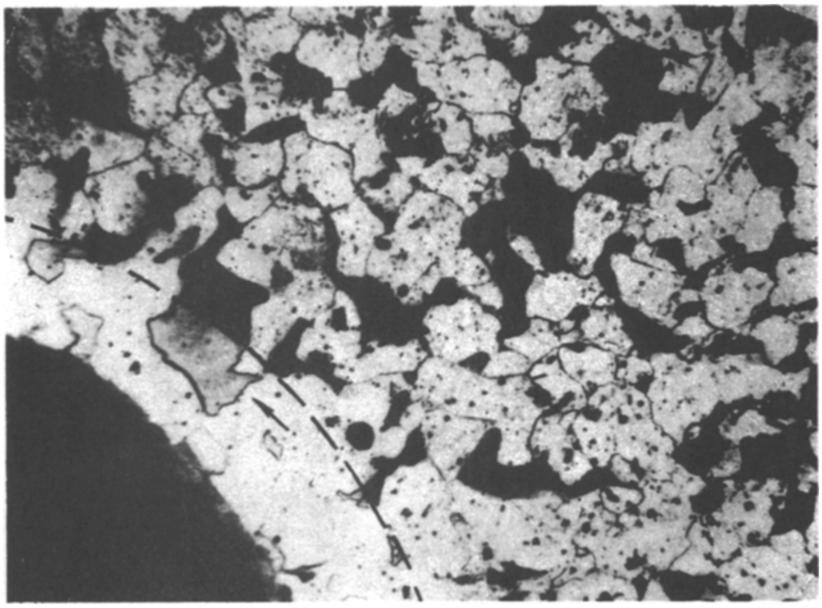

Fig. 5. Showing the clearly defined boundary between the initial structure and the zone subjected to laser radiation.

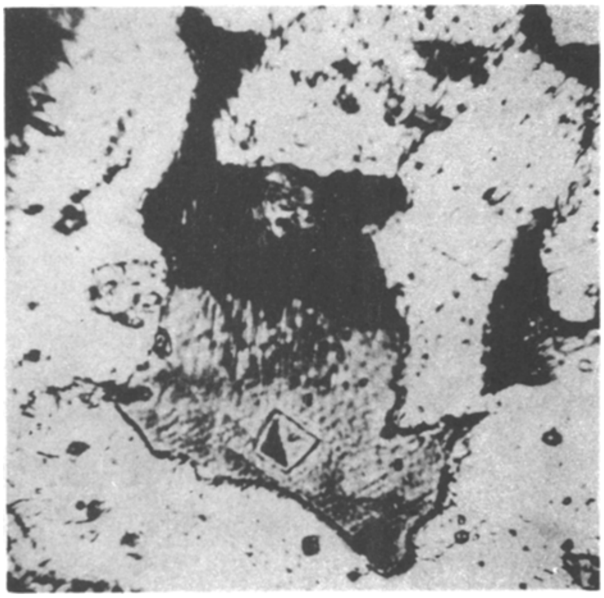

Fig. 6. Showing a pearlite grain divided into two parts, one with the initial and the other with the changed structure.

The boundary is so sharp that several pearlite grains are divided by it into parts with the initial and changed structures. One of these grains is indicated by an arrow in Fig. 5; a photomicrograph of the same grain at higher magnification × 1500), showing diamond pyramid indentations, is reproduced in Fig. 6. The hardness of the black part of this grain is 300 kg/mm^2, which is the usual figure obtained for pearlite grains; the hardness of the white part of the grain exceeds 1000 kg/mm^2.

The presence of these sharp boundaries, not observed after normal heat treatments, is a clear indication of the specific conditions of the propagation of heat waves produced by high-intensity heat pulses.

The increase produced in the microhardness of low-carbon steel by laser radiation is 700 ± 400 kg/mm^2, i. e., the hardness of isolated regions of this steel may be increased by 1100 kg/mm^2. We point out for comparison that 30% reduction by cold work increases the hardness of ferrite by 100/mm^2, and the increase produced in the hardness of low-carbon steel by ordinary water-quenching is only 130 kg/mm^2. None of the conventional thermal or mechanical treatments of steel can increase its hardness by 700 kg/mm^2.

A complex treatment, e.g., thermomechanical hardening, which combines dynamic compression and quenching, may increase the hardness of low-carbon steel by 250 kg/mm^2 [2]; a similar increase, as was previously stated, may be produced by impact at velocities of up to 4000 m/sec.

It may be postulated that the intense hardening effects observed on low-carbon steel are associated with the unusually short time during which the heat energy is generated. It should be pointed out, however, that no twinning is observed in the ferrite grains of low-carbon steel subjected to laser radiation, while impulsive deformation produced by explosive or impact loading at room or subzero temperatures is accompanied by intense twinning. Impulsive deformation of steel specimens at 700° C produced no twinning, but led to the appearance of recrystallized and deformed grains, which are not observed in steel subjected to laser radiation. Consequently, the changes produced by laser beam pulses cannot be attributed to the effects of deformation alone. Let us briefly consider the results obtained for other materials. The increase in hardness in the region of craters on the surface of armco iron is not very large, its hardness increasing from 180 to 260 kg/mm^2, which is similar to the increase produced in the hardness of this material by cold work. In the case of armco iron containing only 0.06% C, however, isolated regions with a hardness of 1100 kg/mm^2 were observed. The hardness of steel U10 (containing 1.0% C) in the initial condition was 380 ± 140 kg/mm^2; the structure formed under the influence of a laser pulse had a hardness of 1000 kg/mm^2, the increase in hardness of this steel (600 kg/mm^2) being slightly lower than in the case of low-carbon steel. In the case of a high-speed cutting steel of complex composition and with high initial hardness (450 ± 50 kg/mm^2), the hardness in the laser irradiated region was only 650 ± 50 kg/mm^2, i. e., the increase in hardness was even less. Consequently, the results of the present investigation supported the previously postulated view [3] that the relative hardening of steel as a result of thermal or mechanical treatment is inversely proportional to its initial hardness attained as a result of alloying.

Tests on a low-melting metal, i. e., tin, showed that craters produced by laser beams in this case are much deeper than on steel; no changes in the structure and hardness of this metal were observed in the crater regions. In the case of duralumin, a slight softening in the crater region was observed; this alloy was the only one among the materials tested in which cracks were formed in the crater region.

In conclusion, the authors would like to thank R. V. Khokhlov for providing the facilities for the experimental work, and G. I. Barenblatt and I. M. Gryuznov for their assistance in interpreting the results.

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