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## INFLUENCE OF LASER RADIATION ON METALS

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A considerable number of works have been published on the investigation of the influence of optical quantum generator (laser) radiation on metals [1-15].

This work was undertaken in order to provide a comparative study of the behavior of a large number of metals under the influence of light fluxes with densities up to $10^5$ w/cm$^2$.

The size of the light spot on the surface of the metal reached 7.5 mm in diameter, allowing a more detailed investigation of the structure and properties of the irradiated surface. Furthermore, in contrast to works published earlier, in this investigation the irradiated specimens were in an evacuated chamber (residual pressure $10^{-4}$ mm hg).

Testing Method. The high energy light source was a GOS-300 device. The wave length is 1.06 mm, the pulse length is about $1 \cdot 10^{-3}$ sec. The light flux was focused by a lens with a focal length of 100 cm. The specimens to be irradiated were placed at $l$ = 75 cm from the lens (in certain cases, $l$ = 85 cm). The calculated cross section of the light beam at this distance was 44.2 and 15.9 mm$^2$ respectively.

The energy of a light pulse was determined in each experiment using a calorimeter [16]. For this, a portion of the light flux (about 10%) was deflected to one side by a glass plate set at 45° to the beam.

Metal specimens 10-12 mm in diamter and 5-6 mm thick were used, in which one end was polished by the ordinary method for preparation of sections (but generally not to mirror smoothness). With the exception of cases where it is particularly noted, the specimens were investigated in their initial state (that is without annealing).

TABLE 1. PHYSICAL PROPERTIES* OF INVESTIGATED METALS AND CRATER DEPTH RESULTING FROM LIGHT BEAM WITH ENERGY DENSITY 50 J/cm²

| a. Metal | b. $T_m$, °K | c. $q_m$, kcal/cm³ | d. $T_b$, °K | e. $q_e$, kcal/cm³ | f. $Q_e$, kcal/cm³ | g. λ, cal/cm·sec·deg | h. a, cm²/sec | i. ρ, % | j. $h_l$, mm |
|---|---|---|---|---|---|---|---|---|---|
| W | 3680 | 1.2 | 6070 | 23.1 | 29.0 | 0.48 | 0.78 | 62 | — |
| Ta | 3270 | 0.6 | 6370 | 16.5 | 22.8 | 0.13 | 0.24 | | — |
| Mo | 2880 | 0.5 | 5070 | 16.8 | 21.3 | 0.35 | 0.53 | 58 | — |
| Nb | 2680 | 0.5 | 3570 | 15.7 | 18.3 | 0.13 | 0.23 | | (0.03) |
| Zr | 2200 | 0.4 | >3200 | 10.5 | 12.7 | 0.04 | 0.10 | | 0.04/35 |
| Cr | 2150 | 0.5 | 2750 | 8.2 | 10.9 | 0.17 | 0.23 | 57 | 0.02/35 |
| Pt | 2050 | 0.6 | 4570 | 13.8 | 18.7 | 0.09 | 0.10 | 73 | (0.02 |
| Ti | 2000 | 0.4 | 3530 | 6.5 | 9.4 | 0.04 | 0.07 | | 0.06 |
| Fe | 1820 | 0.5 | 3500 | 12.5 | 18.0 | 0.16 | 0.20 | 65 | 0.03 |
| Co | 1760 | 0.6 | 3460 | 11.0 | 16.1 | 0.17 | 0.20 | | 0.01 |
| Ni | 1730 | 0.6 | 3350 | 9.1 | 14.4 | 0.14 | 0.18 | 72 | 0.09 |
| Be | 1560 | 0.5 | 2780 | 11.3 | 14.4 | 0.40 | 0.44 | | 0.04 |
| Cu | 1350 | 0.4 | 2630 | 7.7 | 11.3 | 0.92 | 1.12 | 90 | — |
| Ge | 1230 | 0.5 | 2970 | 8.7 | 10.2 | 0.14 | 0.35 | | ~0.10 |
| Ag | 1230 | 0.2 | 2430 | 7.5 | 9.3 | 0.97 | 1.55 | 96 | — |
| Al | 930 | 0.3 | 2330 | 6.1 | 8.0 | 0.50 | 0.87 | 74 | ~0.01 |
| Mg | 920 | 0.2 | 1380 | 2.3 | 2.9 | 0.35 | 0.85 | 74 | ~0.10/20 |
| Zn | 680 | 0.2 | 1180 | 3.0 | 4.4 | 0.26 | 0.41 | 49 | 0.10 |
| Pb | 600 | 0.1 | 1980 | 2.3 | 3.6 | 0.08 | 0.24 | | 0.10 |
| Cd | 580 | 0.1 | 1040 | 2.5 | 3.1 | 0.22 | 0.47 | | 0.10 |
| Bi | 540 | 0.1 | 1750 | 2.0 | 2.8 | 0.02 | 0.08 | | ~1.0/25 |
| Sn | 500 | 0.1 | 2540 | 4.2 | 5.4 | 0.15 | 0.38 | | 0.15 |

Key: a, Metal; b, $T_m$, °K; c, $q_m$, kcal/cm³; d, $T_b$, °K; e, $q_e$, kcal/cm³; f, $Q_e$, kcal/cm³; g, λ, cal/cm·sec·deg; h, a, cm²/sec; i, ρ, %; j, $h_l$, mm.

* $T_m$, $T_b$, melting and boiling points, $q_p$, $q_e$, $Q_e$, latent heat of melting, evaporation and enthalpy (heat content); λ, coefficient of heat conductivity (at 20°C); a, coefficient of temperature conductivity (at 20°C); ρ, reflection factor at λ = 1 μ; $h_l$, crater depth (denominator of fraction indicates energy density if other than 50 J/cm², numbers in parentheses indicate data produced in irradiation of thin specimens, thickness 0.2-0.3 mm).

One or more specimens were placed in a molybdenum glass test tube 15 mm in diameter (wall thickness 1.8 mm). Before irradiation of the test tube with specimens, it was evacuated to a residual pressure of $10^{-4}$ - $10^{-5}$ mm Hg. Irradiation was performed through the glass wall of the test tube, after which the specimens were removed from the test tube and the microhardness was measured (using a PMT-3 device with a load of 100 g) and the microstructure was investigated.

TABLE 2. DATA* ON IRRADIATION OF METALS AND ALLOYS WITH VARIOUS RADIATION ENERGY DENSITIES

| a. № | b. Металл | c. δ, Дж/см² | d. d, мм | e. $h_1$, мм | f. $h_2$, мм | g. $d_c$, мм | h. Вид плавления |
|---|---|---|---|---|---|---|---|
| 1 | W | 50 | — | — | — | — | k Н. |
| 2 | W | 75 | 1÷2 | 0.01 | 0.01 | 3÷4 | l Б. л. |
| 3 | W | 120 | 2÷3 | 0.01 | 0.10 | 4 | m Л. |
| 4 | Ta | 50 | — | — | — | — | k Н. |
| 5 | Ta | 120 | 3÷4 | 0.10 | 0.07 | 5÷6 | m Л. |
| 6 | Mo | 50 | — | — | — | — | k Н. |
| 7 | Mo | 75 | 2.5÷3 | 0.01 | 0.03 | 6 | l Б. л. |
| 8 | Mo | 85 | 3 | 0.01 | 0.04 | 6 | m Л. |
| 9** | Mo | 85 | 1 | <0.01 | <0.01 | 4 | l Б. л. |
| 10** | Mo | 120 | 3÷4 | 0.04 | 0.06 | 10 | m Л. |
| 11 | Pt | 40 | — | — | — | — | k Н. |
| 12 | Pt | 50 | 2÷3 | 0.02 | 0.07 | — | l Б. л. |
| 13 | Fe | 25 | 2÷2.5 | 0.02 | 0.02 | — | l Б. л. |
| 14 | Fe | 50 | 3.5÷4 | | | 7 | » |
| 15 | Fe | 75 | 5÷6 | | | 12 | m Л. |
| 16 | Y8 | 25 | 3.5 | 0.02 | 0.03 | — | l Б. л. |
| 17 | Y8 | 50 | 3÷4 | 0.02 | 0.06 | 1 | » |
| 18 | Y8 | 80 | 5÷6 | 0.07 | 0.10 | 12 | m Л. |
| 19 | X18 | 50 | 3÷4 | 0.10 | 0.05 | 6 | » |
| 20 | X18 | 90 | 7 | 0.10 | 0.10 | 13 | » |
| 21 | Be | 50 | 3÷4 | 0.04 | 0.02 | 5÷6 | l Б. л. |
| 22 | Be | 60 | 4÷5 | 0.06 | 0.03 | 10÷12 | n Л. п. |
| 23 | Cu | 90 | — | — | — | — | k Н. |
| 24 | Cu | 310 | 1 | 0.01 | 0.01 | | l Б. л. |
| 25 | i Латунь | 40 | — | — | — | — | k Н. |
| 26 | i Латунь | 170 | 6.5 | 0.07 | 0.17 | 12÷15 | n Л. п. |
| 27 | j ДТ16 | 50 | 2 | 0.01 | 0.01 | | » |
| 28 | j ДТ16 | 75 | 4 | 0.05 | 0.04 | | » |
| 29 | Zn | 25 | 3÷4 | | | (—) | m Л. |
| 30 | Zn | 50 | 4÷5 | 0.10 | 0.20 | (5÷6) | » |
| 31 | Cd | 25 | 6 | 0.05 | 0.25 | — | » |
| 32 | Cd | 50 | 6÷7 | 0.10 | 0.25 | — | » |
| 33 | Bi | 25 | ~9 | ~1.0 | | 8÷10 | » |

Key: a, Number; b, Metal; c, δ, j/cm²; d, d, mm; e, $h_1$, mm; f, $h_2$, mm; g, $d_c$, mm; h, Form of Melting; i, Brass; j, DT16; k, N; l, Nc; m, C; n, Cf.

* Symbols (see Figure 1): d, crater diameter; $h_1$, crater depth; $h_2$, crater wall height; $d_c$, diameter of zone of glass cracking; in last column: N, no melting; Nc, melting, no crater; C, crater; Cf, crater with flat wall top.

**Monocrystals, surface subjected to chemical polishing.

Table 1 presents some handbook data for the metals which were irradiated, and the depths of craters formed on the surface as a result of the action of light with a specific energy of 50 j/cm$^2$. Most of the metals used were technically pure (99.95% W, 99.1% Ta, 99.97% Mo, 99.1% Nb, 99.99% Zr, 99.8% Pt, 99.6%, Ti, Fe + 0.04% C, 99.9% Ni, 99.3% Be, 99.92% Cu, 99.999% Al, 99.9% Cd, 99.999% Bi).

It was assumed that about 10% of the radiant energy failed to reach the specimen as a result of losses to absorption and reflection in the glass of the test tube. Table 2 presents data on the nominal light energy densities (δ) used, with corrections for losses in the glass. Obviously, a significant portion of the light energy was reflected by the surface of the metal. The value of the reflected energy depends on the physical nature of the metal (see Table 1) and the state of its surface before radiation and during radiation. These losses of energy were not taken into consideration.

Results of tests. When light radiation with a specific energy of 50 j/cm$^2$ or more (Tables 1 and 2) acts on the polished surface of most of the metals investigated, a crater with melted surface is formed (Figure 1). The diameter and depth of the crater varies both upon transition from one metal to another, and with a change in the specific light energy. In most cases, in metals with higher values of enthalpy, the diameter and depth of the crater were less than in low melting point metals. Furthermore, the radiation energy indicated above in the case of such refractory metals as W, Ta and Mo, was increased to 75 j/cm$^2$ and higher, and at first (as in the case of the other metals) melting of the surface was not accompanied by the formation of a crater (Figure 2, a).

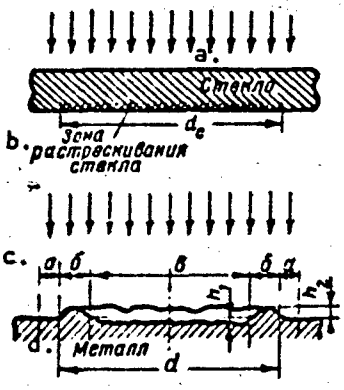


Figure 1. Diagram of Crater on Surface of Specimen.

Key: a, Glass; b, Zone of cracking of glass; c, a - b - c - b - a; d, Metal.

With a specific energy somewhat lower than the value causing melting, the surface scratches remaining after polishing disappeared, and the microstructure of the metal (grain boundaries, etc.) could be seen.

With a specific energy of 75 j/cm$^2$ for W and Mo (as well as Armco iron and U3 steel at 25-50 j/cm$^2$) the diameter of the melted zone was not great (it was considerably less than the calculated diameter of the light spot). The formation of a crater occurred only with rather strong gas dynamic action on the liquid metal resulting from an increase in the quantity of metal evaporated. As the specific energy increased, the diameter of the crater was increased, reaching its limiting value, corresponding to the approximate diameter of the light spot, with a simultaneous increase in the depth of the crater. The melted surface of the crater and the circular crater wall showed traces of high temperature etchings, as a result of which the microstructure of the metal (grain boundaries, twins, etc.) could be seen. Furthermore, probably as a result of this same process the surfaces of the grains frequently showed a cellular (block) structure with the smaller cell dimension being about 0.1 mm, probably related to rapid cooling. A larger (up to 1 mm) block structure was noted in the irradiated copper (in the melting zone), each grain of the metal having a block structure with a definite orientation (Figure 3). Irradiated Bi and Ge showed manifestation of a stepped, lamellar structure.

It should be noted that (as follows from the data of Table 1), the majority of all the thermal energy, into which most of the absorbed light energy is transformed when the light interacts with the metals [3], should go not so much to heating and melting of the metal, as to its evaporation. This conclusion follows from a comparison of the latent heat of evaporation and the heat content, which in this work was calculated as the thermal energy required to heat the metal from 20°C to the melting point and evaporate 1 cm$^3$ of the metal (with a certain mean value of heat capacity).

Thus, the greatest heat resistance should be that of metals with the greatest latent heat of evaporation. However, in the case of relatively low radiation energies, causing only the appearance of a melted surface layer, the quantity of metal evaporated may be slight, and, consequently, the share of thermal energy used in this process may also be slight. The resistance of the metal under these conditions will be determined by the melting point, more precisely by the enthalpy at this temperature.

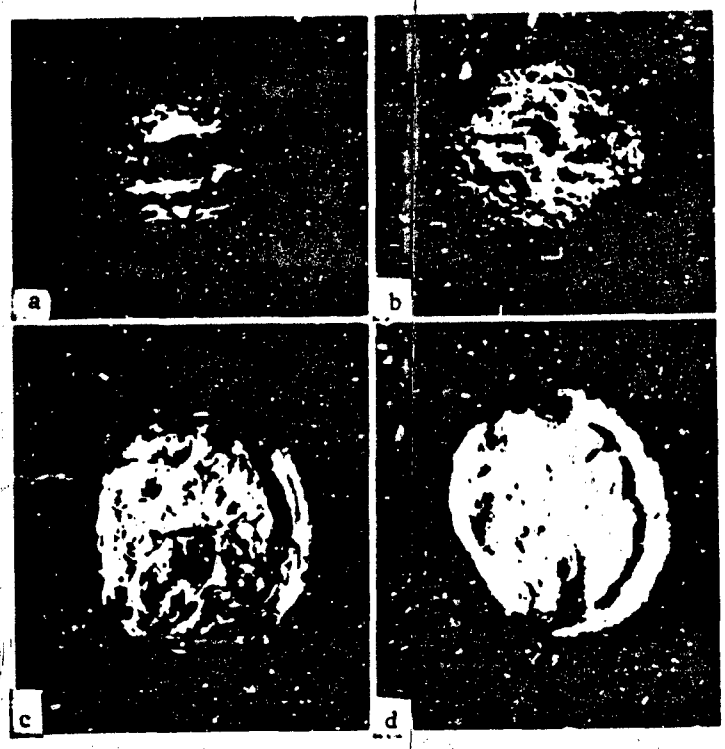


Figure 2. Surface (×8) of Specimens of Iron (a, c: 0.04% C) and Steel (b, d: 0.8% C) After Irradiation By Light With Energy Density 50 (a, b) and 75 (c, d) j/cm$^2$; a, Banded Structure of Melted Zone is a Result of the Influence of Heterogeneities in the Glass of the Sample Tube.

It follows from the data of Table 2 that in easily melted metals, the melting of the surface will probably occur at a specific light energy of 5-10 j/cm$^2$ (since at 25 j/cm$^2$ a considerable crater was formed and notable evaporation occurred). Thus, the critical value of specific radiation energy causing melting and partial evaporation for all metals apparently will be in the range of $5\text{-}5\cdot10^2$ j/cm$^2$ (upper limit for Ag and Cu - see below), that is $5\cdot10^3\text{-}5\cdot10^5$ w/cm$^2$, which is 2 to 3 orders of magnitude below the values produced in [3] (calculated for individual

peaks of the laser pulse). Quite possibly, the values produced in our work were too low for a number of reasons (for example, due to irregularities in the distribution of light flux density through the cross section of the beam, insufficient reflecting capacity of the metal surface after polishing, etc). At the same time, the data presented in a number of other works (as in [3]) are related either to the case of the action of a focused laser beam, or are produced for shorter exposure times to the radiation (for example, action of a laser with modulated quality). Both doubtless might lead to different physical phenomena [9] and different values of threshold energy.

As an exception to the general rule of the behavior of metals when irradiated with high energy light, we should note that copper and particularly silver were the most highly resistant of all the metals investigated, including the refractory metals. Only with a specific energy of about 300-350 j/cm$^2$ (with $l$ = 85 mm) did a noticeable melting spot (1-2 mm in diameter) appear on the surface of the copper specimen (the formation of a crater was observed at 400 j/cm$^2$ with specimen thickness 0.5 mm).

Figure 3. Microphotograph (×340) of Sector of Surface of Copper Specimen After Irradiation: Columnar and Cellular Structure of Dendrites Formed Upon Hardening of Melted Metal Can Be seen.

The same factor (that is high temperature conductivity) can explain the comparatively weak action of radiation on pure aluminum and aluminum alloy DT16A. Conversely, the low values of temperature conductivity of Zr, Ti, Kh18N25S2 and Bi probably lead to the increased depth and diameter of craters in these metals in comparison with metals which were similar in all other heat physical properties (with the same specific light energy).

It follows from the data presented above that the critical value of specific radiation energy leading to melting and partial evaporation depends, in addition to everything else, both on the reflective capacity of the irradiated surface and on the conditions of heat transfer away from the surface. The latter are determined by the temperature conductivity of the material, the geometry of the specimen, and its thickness. Under our experimental conditions, specimens of copper and silver of 0.5 mm and greater in thickness can be considered rather massive.

When cast, coarse grained germanium of relatively low purity was irradiated by light with an energy of 25 j/cm$^2$, melting of the surface and disruption (cracking) of the specimen were observed. In the case of irradiation of purer, dislocation-free monocrystals of germanium, melting and cracking occurred in the surface layers with simultaneous separation of individual sectors about 0.05 mm in thickness. The formation of cracks on the surface of the metal melted upon irradiation was observed (under the microscope) for a number of other metals as well: W, Mo, Cr, Ti, Kh18N25S2, Be, DT16A, the cracking occurring primarily along grain boundaries.

If the surface of a copper specimen was dusted with black, at an energy of 75 j/cm$^2$ we observed significant melting, evaporation and spraying of liquid metal. About 200 j/cm$^2$ was significant to cause melting of a copper specimen oxidized on the surface. We can conclude from this that the resistance of copper (and silver) results primarily from the high reflecting capacity of these metals.

On the other hand, when a thin copper strip 0.07 mm was irradiated, when heat transfer into the depth of the metal was limited, melting clear through, forming an aperture 2.00 mm in diameter occurred at 90 j/cm$^2$. Thus, we must assume that the high heat conductivity (or temperature conductivity) of copper and silver are important, increasing the threshold value of radiation energy leading to melting and evaporation. It follows from this also that we cannot ignore heat transfer into the depths of the metal (as is done in [3]) during the time of action of the pulse ($10^{-3}$ sec). When plates of copper and silver 0.2 mm thick are irradiated (in the air) with a specific light energy of 50-55 j/cm$^2$, hardly noticeable oxidation of the surface and warping of the plate in the radiation zone occur. At 70-80 j/cm$^2$ (Cu) and 80-100 j/cm$^2$ (Ag), melting of the surface in the center of the irradiated zone was noted. However, burn through with formation of a hole occurred only at 200-240 j/cm$^2$ (Cu) and 350-400 j/cm$^2$ (Ag). Under the same experimental conditions (200 j/cm$^2$) irradiation of a massive copper specimen (4-5 mm thick) was accompanied only by weak oxidation of its surface (without indications of melting and evaporation).

When monocrystals of molybdenum and beryllium were irradiated, cracks in and around the melting zone formed along certain crystalographic directions. The melted surface of many irradiated metals showed traces of plastic deformation (twins, shear lines, etc).

Microstructural investigations of the zone melted by radiation indicated that in addition to the visually observable details of the crater, the crater floor and the circular walls, there is a circular area near the outer edge of the wall (area a on Figure 1) which should be differentiated. Within this area, disappearance of scratches remaining after polishing of the surface occurred, along with formation of a small grain structure (diameter 1-10 mm), although surface melting in this zone (with the exception of individual points) did not occur. The boundaries of this area changed significantly upon transition from one sector of the radiated surface to another.

As a result of the radiation, apparently, evaporation of a portion of the metal from the surface occurred (high temperature etching) along with recrystallization of the thin layer work hardened upon polishing with the formation of the fine grain structure.

A grain also appeared on the melted surface of the crater, but its size was greater (10-100 mm and more - approaching the size of the initial grain). When thin metal plates (Cu, Pt, Ag) 0.07-0.2 mm were irradiated, the formation of a comparatively large, non-equilibrium grain was observed, extended along the radius from the center of the crater in correspondence with the direction of maximum heat transfer (to the side). Figure 3 shows a microphotograph of an irradiated sector of the surface of a copper strip 0.07 mm in thickness. As a result of melting, partial evaporation and subsequent hardening, a thin metal film about 1 mm in diameter was produced. The microphotograph shows the complex surface structure of this film: the large grain extended along the radius of the crater and the related complex cellular dendritic structure within the grains. Along the edges of the crater we can see an equiaxial grain (outside the melting zone) and drops of sprayed metal. A similar picture was observed on the opposite side of the specimen.

As follows from the data of Table 3, of all the metals investigated, a sharp increase in microhardness resulting from irradiation was observed only in U8 steel (see also [7, 8, 10]). Here, in surface layers about 0.05 mm thick, Martensite structure was noted (along with residual austenite). The increase in microhardness and change in microstructure apparently resulted from rapid cooling. A notable increase in hardness was also noted for irradiated Armco iron (the hardness was increased by about 2 times, the same as when irradiated in air, see [7]), in

chromium and titanium (by 50%). In the remaining metals, the increase in hardness did not exceed 10-20%. It should be noted that in this work, the change in microhardness in most cases was compared to the initial value for the polished surface, which was considerably work hardened during polishing. This fact made determination of the hardening effect during irradiation more difficult.

TABLE 3. MICROHARDNESS OF METALS IN THE INITIAL STATE, AFTER IRRADIATION (FOR LOCATION OF ZONES SEE FIGURE 1) AND AFTER ANNEALING

| a. № | b. Металл | c $H_\mu$, кг/мм², в состоянии | | | | | a. № | b. Металл | c $H_\mu$, кг/мм², в состоянии | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | d. исходном | e. облученном | | | i. отожженном | | | d. исходном | e. облученном | | | i. отожженном |
| | | | f. a | g. b | h. c | | | | | f. a | g. b | h. c | |
| 1 | W | 470 | 370 | 410 | 410 | 330 | 14 | Co | 245 | 210 | 245 | 240 | — |
| 2 | Ta | 270 | 240 | 230 | 210 | 250 | 15 | Ni | 130 | 122 | 130 | 105 | — |
| 3* | Mo | 180 | 200 | 290 | 180 | — | 16* | Be | 125 | 140 | 160 | 150 | — |
| 4 | Mo | 250 | 230 | 230 | 220 | 210 | 17** | Be | 200 | 200 | 250 | 240 | 200 |
| 5 | Nb | 235 | 220 | 370 | 245 | — | 18 | Be | 275 | 300 | 250 | 260 | — |
| 6 | Zr | 215 | 225 | 260 | 200 | — | 19** | Cu | 52 | 58 | 62 | 55 | — |
| 7 | Cr | 215 | 245 | 300 | 285 | — | 20 | Al | 25 | 30 | 25 | 20 | — |
| 8 | Ti | 310 | 320 | 470 | 380 | 280 | 21 k | ДТ16 | 150 | 100 | 110 | 110 | — |
| 9 | Fe | 140 | 180 | 300 | 180 | — | 22 | Mg | 50 | 45 | 46 | 55 | — |
| 10** | Fe | 110 | 210 | 230 | 230 | — | 23 | Zn | 45 | 40 | 45 | 47 | — |
| 11 | Y8 | 250 | 600 | 900 | 1000 | 180 | 24 | Pb | 65 | 50 | 60 | 55 | — |
| 12 i | X18... | 260 | 220 | 230 | 220 | — | 25 | Sn | 95 | 90 | 110 | 90 | — |
| 13* j | X18... | 190 | 210 | 180 | 210 | — | | | | | | | |

Key: a, Number; b, Metal; c, $H_\mu$, kg/mm$^2$, in states; d, Initial; e, Irradiated; f, a; g, b; h, c; i, Annealed; j, Kh18; k, DT16.

* Monocrystals: Mo in annealed state in plane (001), Be in plane (0001).
**In annealed state (Cu with load 20 g).

Many irradiated metals were subjected to X-ray structural investigation. In Armco iron (0.04% C), considerable erosion of the α-Fe lines was observed (mean size of blocks was about 100 Å, distortion of lattice period $\Delta a/a \simeq 3 \cdot 10^{-2}$). This strong expansion of the line may result from the formation of tetragonality in the lattice of the tempered α-Fe. This distortion of the lattice could arise in local areas with increased carbon concentration. The presence of lines of an additional phase (apparently cementite) in annealed iron and their disappearance after irradiation indicates the possibility of this mechanism. The

irradiation of the Armco iron, like U8 steel, was accompanied by the same effect observed upon etching in 10-20% alcoholic solutions of nitric acid: the irradiated (melted) portion of the surface was rapidly etched and darkened, like the surface of steel hardened by the ordinary method.

X-ray structural analysis of irradiated titanium specimens (99.6% Ti) also showed strong erosion of the lines. No expansion of the lines was noted in the case of irradiated specimens of copper (99.92% Cu) aluminum (99.999% Al) or aluminum alloy D16A.

Thus, on the basis of the data presented above we can conclude that the hardening of the surface layer heated upon irradiation due to heat transfer into the depth of the metal (that is due to quenching) is not great in most cases. However, in some individual cases essential distortion of the lattice and reduction in grain size does occur, accompanied by an increase in hardness. This is apparently facilitated (as in ordinary quenching) by the presence of impurities with variable solubility and allotropic conversions. An additional reason for increasing hardness might be plastic deformation, traces of which can be frequently observed on the irradiated surface.

In irradiation of metals placed in an evacuated sample tube of glass (or in irradiation in air through a glass plate) it was discovered that a thin layer (about 0.05 mm) of the inner surface of the glass located opposite the irradiated metal surface at a distance of about 5 mm, is cracked, with the formation of a fine grid of cracks (this cracking did not occur when specimen tubes of quartz were used). The dimensions of the area of cracking in the surface layer of the glass (with the formation of cells about 0.1-0.5 mm in diameter) varied from a hardly noticeable dot to a spot 12-15 mm in diameter depending on the radiation energy and the nature of the metal. As a rule, if melting of the surface of the metal did not occur, the cracking was also not observed. In the case of the refractory metals (W, Ta, Mo) cracking also occurred as the surface was melted, although darkening of the walls of the tube due to evaporated metal was not noticed. In this case (as for many other metals) the mean diameter of the cracked area was almost equal to the mean diameter of the melted zone.

Upon transition to more easily melted metals or with increasing radiation energy, as the crater diameter increased, the diameter of the cracked glass area also increased, but the change in the glass area occurred more rapidly, so that in the limiting case it was approximately twice as wide as the diameter of the crater and, consequently, exceeded the diameter of the light spot (see Table 2). It is interesting that in

the case of Zn and Cd, in spite of the intensive evaporation with precipitation of the evaporated metal on the walls of the flask, cracking was not observed in every experiment.

When the light was shined at an angle of 45° to the surface of the metal, the cracking area was not located perpendicular to the surface of the specimen (drawn from the center of the crater), but was displaced toward the area of the glass illuminated by the entering beam. When a copper plate 0.5 mm thick was irradiated in a glass tube at an angle of 45° to the surface of the metal with a radiant energy density of 350-400 $j/cm^2$, the copper was melted and cracking of the internal surface of the glass was produced both where the beam entered the glass and at the exit point of the reflected beam. It was also determined that this cracking of the glass in some experiments did not occur immediately after irradiation, but after one or several minutes following irradiation.

The data on cracking of glass presented above indicate that this phenomenon is related to precipitation of particles of the evaporated metal on the surface of the glass in quantities and with energy sufficient to cause local heating and stressing. Additional liberation of heat may also occur as a result of absorption of light energy during the process of irradiation by particles of metal condensed on the surface of the glass after evaporation from the surface of the metal. We can also assume the existence of an interaction between the radiation and metal vapors, as a result of which a plasma column may arise along the path of the beam. In this case, cracking of the surface layer should be looked upon as a result of the action of the particles of this plasma on the glass.

## Conclusions

1. An investigation was performed of the influence of laser radiation in the free generation mode ($\lambda = 1.06$ mm, $\tau = 1 \cdot 10^{-3}$ sec) on 28 metals and alloys in a vacuum with irradiation of the polished metal surface by a broad beam.

With a specific radiated power of about $5 \cdot 10^3$-$5 \cdot 10^5$ $w/cm^2$ (without considering the peak structure of the laser pulse) in most metals we observed melting of the surface and partial evaporation, revealing the microstructure. With a somewhat smaller value of power of the light pulse, local evaporation of the metal occurred.

2. The resistance of the metals to the action of the powerful light beam depended (with the given illumination conditions) on the reflective capacity of the metal surface, as well as the heat content (enthalpy) of the metal at the boiling point (or melting point with small quantities of evaporated metal) and, finally, on the conditions of heat transfer away from the illuminated surface.

3. As a result of heating of a thin surface layer of the metal under the influence of the light pulse and its rapid cooling due to heat transfer into the volume in many metals hardening occurred in the surface layers, leading to an increase in microhardness (in U8 steel, Armco iron, chromium, titanium, etc). X-ray investigations showed that in these cases after irradiation, strong expansion of the lines occurred. At the same time, in many other metals no essential hardening or distortion of the microstructure as a result of radiation was noted. It is assumed that the increase in hardness resulting from quenching in the surface layers of the irradiated metal can occur as a result of impurities with variable solubility and in the presence of allotropic conversions.

4. Some data have been accumulated on the interaction of metal vapors with the surface of the glass located over the illuminated metal.

## BIBLIOGRAPHY


1. Rykalin, N. N., Krasulin, Yu. L., "Estimation of Energy Parameters of Welding of Metals By Laser Light Beam," *DAN SSSR*, Vol. 163, No. 1, p. 87, 1965.

2. Rykalin, N. N. and Uglov, A. A. "Heating of Thin Sheets During Laser Welding," *DAN SSSR*, p. 165, No. 2, Vol. 319, 1965.

3. Anisimov, S. I., Bonch-Bruyevich, A. M., et al, "The Action of Powerful Light Beams on Metals," *Zh. tekhn. fiz.*, p. 36, No. 7, Vol. 1273, 1966.

4. Basov, N. G., Boyko, V. A., et al, "Heating and Disintegration of a Plasma Formed by the Action of a Focused Gigantic Laser Pulse on a Solid Target," *Zh. eksperim. i teor. fiz.*, Vol. 51, No. 4, p. 989, 1966.

5. Ready, J. F., "Effects Due to Absorption of Laser Radiation," *J. Appl. Phys.*, Vol. 36, No. 2, p. 462, 1965.

6. Ulyakov, P. I., "Some Regularities in the Disruption of Solid Media by Laser Radiation," *Zh. eksperim. i teor. fiz.*, Vol. 52, No. 3, p. 820, 1967.

7. Aver'yanova, T. M., Mirkin, L. I., et al, "The Action of Intensive Light Beams on a Metal Surface," *PMTF*, No. 6, p. 84, 1965.

8. Mirkin, L. I., Pilipetskiy, N. F., "The Physical Nature of the Hardening of Steels Under the Influence of Light Pulses," *DAN SSSR*, Vol. 172, No. 3, p. 580, 1966.

9. Kalmykov, A. A., Nemchinov, I. V., et al, "Experimental Investigation of the Disintegration of Instantaneously Heated Material and Impulse Formed at Energy Concentrations Less Than the Heat of Evaporation," *PMTF*, No. 6, p. 3, 1966.

10. Kokora, A. N., Zhukov, A. A., et al, "Laser Beam Treatment of Steel," *MiTOM*, No. 2, p. 41, 1966.

11. Braginskiy, V. B., Minakova, I. I., et al, "Some Mechanical Effects Upon Interaction of Pulsed Electromagnetic Radiation and Metals," *Zh. tekhn, fiz.*, Vol. 37, No. 6, p. 1045, 1967.

12. Murphy, R. J., Ritter, G. J., "Laser-Induced Damage in Copper Crystals," *J. Appl. Phys. Letters*, Vol. 7, No. 9, p. 272, 1966.

13. Vogel, K., Backlund, P., "Application of Electron and Optical Microscopy in Studying Laser-Irradiated Metal Surfaces," *J. Appl. Phys.*, Vol. 36, No. 12, p. 3697, 1965.

14. Thiessen, P. A., Meyer, K., Meier, W., "Structural Changes in Antimony Crystals by Point Mechanical Working and Laser Beam," *Monatsber. Deutsch. Acad. Wiss.*, Berlin, Vol. 7, No. 5-6, p. 391, 1965.

15. Murphy, R. J., Ritter, G. J., "Laser-Induced Thermal Etching of Metal and Semiconductor Surfaces," *Nature*, pp. 210, 5032, 191, 1966.

16. Shestopalov, L. M., Alekseyev, N. I., "A Mirror Calorimeter," *Pribory i tekhnika eksperimenta*, No. 1, p. 170, 1968.

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~~This~~ work presents a comparative study of the behavior of a large number of metals under the influence of light fluxes with densities up to $10^5$ w/cm$^2$. The structure and properties of the irradiated surface are analyzed. The experimental procedures are described.

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| Microstructure of metals | | | | | | |
| Irradiated metal | | | | | | |
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