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CHANGE IN THE STRUCTURE OF THE ALLOY KhN57KVYu UNDER THE ACTION OF SHOCK WAVES GENERATED BY THE ACTION OF POWERFUL NANOSECOND LASER PULSES

R. E. Krzhizhanovskii, V. M. Mikushev, A. A. Nikitin, E. V. Potipalova, Yu. V. Sud'enkov, and N. T. Travina

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We have calculated and experimentally measured the amplitudes of shock waves generated in the monocrystals of the nickel alloy KhN57KVYu under the action of powerful nanosecond laser pulses. We employed an electron-microscope method to study the defect structure formed at various depths of the layers deformed by the shock waves.

When powerful laser pulses interact for brief periods of time with a metal surface, extremely high pressures may be generated within the metal [1, 2, etc.]. The energy absorbed in this case is transferred by the shock waves into the volume of the metal. In this case, if the amplitude of the shock wave exceeds the maximum yield stress of the material, the shock wave will result in plastic deformation at depths considerably greater than that of the thermal heating layer for so long as the action of the pulse is maintained.

It has been established that the direct action of a powerful laser pulse on the surface of a solid cannot produce a high pressure level within the test material, and this is associated with the high rate of vaporization product expansion. Therefore, in order to increase the pressure pulse we resort to treatment beneath a layer of dielectric materials or fluids transparent to laser radiation and this is done in conjunction with a layer of materials which are strong absorbers of laser radiation. Thus, in the capacity of these experimental materials capable of absorbing the laser pulse we used metal foils equal in thickness to the depth of heat-wave penetration during the effective action of the pulse, defined as $\sqrt{\alpha\tau}$, where α is the coefficient of thermal diffusivity; τ is the duration of the light pulse. Utilization of such absorbing layers, given relatively low levels of radiation intensity ($\sim 10^9$ W/cm^2), makes it possible to achieve pressures on the order of 10 GPa [7].

The amplitude of the pressure pulse which arises as a consequence of the brief laser pulses can be calculated [3].

I. P. Bardin Metal-Physics Institute TsNIIchermet, Moscow. P. Togliatti Engineering Economics Institute, Leningrad.
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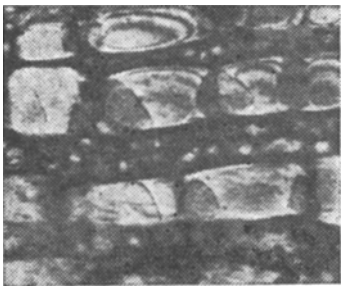

Fig. 1. Electron-microscope image of KhN57KVYu structure after heat treatment (initial state). × 40,000.

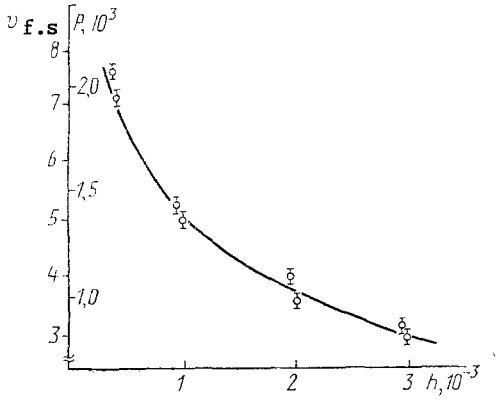

Fig. 2. Experimentally measured pressure amplitudes arising in the alloy KhN57KVYu after treatment with nanosecond laser pulses. $v_{f.s.}$, m/sec; P, bar; h, m.

TABLE 1. Experimental Values of Densities and Velocities for Longitudinal Ultrasonic Waves

Material	Density ρ, g/cm³	Velocity of longitudinal ultrasonic wave v, m/sec
Plastic	1,18	2800±50
Aluminum	2,68*	6260*
Alloy KhN57KVYu	8,60	6220±30

*These values have been taken from the table in [6].

Owing to the complexity of the physical pattern of interaction between the radiation and the actual material, the indicated estimates can only be approximate, particularly in those cases when we are dealing with the action of laser pulses on multiphasic alloys as opposed to pure metals. Therefore, in order to understand the structural changes taking place within the metallic alloys under the action of emitted laser pulses, it is a good idea to undertake an experimental measurement of the pressure pulse amplitude.

It is the purpose of the present study to compare the theoretical and experimentally measured magnitudes of the amplitudes for the shock waves formed in the alloy as a consequence of the action of the nanosecond laser pulses, as well as to study the nature of the structural changes as a result of the plastic deformation caused by the shock waves.

Materials and Methods of Investigation. The study was carried out on monocrystals of the heat-resistant nickel alloy KhN57KVYu. Prior to the laser treatment, the specimens were subjected to thermal annealing in accordance with the following regime: 1160°C, 5 h air cooling + 1050°C, 2 h air cooling + 850°C, 16 h air cooling. As a result of this annealing the alloy structure consisted of a fcc γ-solid solution (matrix) and $LI_2\gamma'$-particle ordering (of the Ni_3Al type).

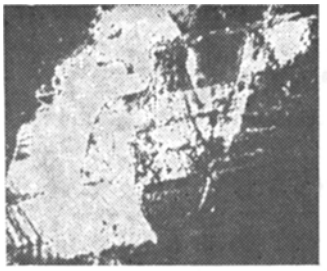

Fig. 3

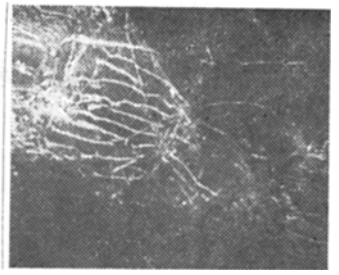

Fig. 4

Fig. 3. Electron-microscope image of slippage bands, light field. × 37,000.

Fig. 4. Electron-microscope image of dislocation structure formed in large (~0.5 μm) particles of the γ' phase under the action of a shock wave, dark field in reflex III of the matrix. × 50,000.

Here the γ'-phase participates morphologically in two forms: 1) large particles (with dimensions of 250-500 nm) cuboidal in shape or in the form of parallelepipeds; 2) small equilibrium particles (30-50 nm) uniformly distributed in the interlayers of the matrix (Fig. 1).

The alloy was subjected to laser treatment by means of pulses generated from a neodymium glass laser, lasting for τ = 25 nsec, with an energy of approximately 5 J and a wavelength of $\lambda = 1.06 \cdot 10^{-6}$ m.

To prevent the dispersion of the plasma, the experiments were conducted in a special plastic cell. The specimen surface was covered with aluminum foil considerably greater in thickness than the absorbing layer. To maintain reliable acoustic contact, we used a silicon lubricant and clamped the treated block to the plastic.

To determine the shock-wave amplitude directly in the specimen, we have to take into consideration the reflection of the radiation at the boundary separating the aluminum from the specimen. The expressions for the transmission coefficient can be written in the form: $P_1/P_2 = 2/(1 + \rho_1 u_1/\rho_2 u_2)$, where P_1 is the amplitude of the wave incident at the boundary between the two media; P_2 is the amplitude of the wave passing through the specimens; $\rho_1 u_1$ and $\rho_2 u_2$ are the acoustic impedances of the aluminum and the specimen. To determine the acoustic impedance of the specimens made of the test alloy KhN57KVYu we measured the velocity of the longitudinal ultrasonic wave (at frequencies of 10-30 MHz) by using the Makskimen [4] pulse-phase precision method. The density of the studied specimens is determined by suspension in a fluid of known density.

A calorimetric method was used during the course of the experiment to monitor the laser pulse energy. The flux density of the laser emission was $q = 10^9$ W/cm^2 (at a beam diameter of $d = 5 \cdot 10^{-3}$ m).

The method of laser interferometry [5] was used experimentally to measure the amplitudes of the shock waves formed in specimens of the alloy KhN57KVYu. We measured the displacement of the free surface for the specimen and we determined the velocity $v_{f.s.}$ of this displacement for specimens of various thicknesses. We estimated the amplitude P from the formula

$$P = \rho u \frac{v_{f.s}}{2}. \tag{1}$$

We studied the structures of specimens subjected to powerful laser pulses by means of luminescent electron microscopy with a JEM-200CX microscope with an acceleration voltage of 200 KeV. The foil was cut with an electrospark unit and finished by mechanical and electrolytic polishing.

Experimental Results and Discussion. The theoretical amplitudes of pressures P generated by laser pulses can be estimated from the following formula, taken from [3]:

$$P = q \frac{\gamma - 1}{\gamma} \frac{\rho_1 u_1 \rho_2 u_2}{\rho_1 u_1 + \rho_2 u_2}, \tag{2}$$

where γ is the effective adiabatic exponent of the plasma being formed, and in accordance with the data from [6] falls within the limits of 1.1-3.0 for all metallic materials. The values of the remaining quantities contained in the formula have been determined experimentally and are presented in Table 1.

The estimate of the amplitude of the pressure pulse P on the basis of formula (2) yields $(2.5\text{-}6.5)\cdot10^4$ bar.

The values of the pressure amplitudes measured experimentally for specimens of the alloy KhN57KVYu, of various thicknesses, can be found in Fig. 2. Comparison of the pressure-amplitude values calculated from formula (2) against the results obtained in measurements on the specimens and carried out in accordance with the above-described method shows that the theoretical values considerably exceed the experimental amplitude values.

The real pressure amplitudes are greater than the values for the stresses corresponding to the maximum yield stress of the alloy and in the specimens we find plastic deformation. The electron-microscopic study of the defect structure formed as a consequence of plastic deformation generated by the shock waves has been carried out for specimens subjected to the action of waves with an amplitude of 10^3 and $2\cdot10^3$ bar. Quantitatively to measure the amplitude of the plastic deformation proves to be impossible, but it is natural that the larger pressure amplitude is matched by a greater degree of plastic deformation and, consequently, a more fully developed defect structure.

With a pressure amplitude of 10^3 bar the defect density is comparatively low and in electron-microscope photographs it becomes possible, at individual points, to establish therefore the various types of defects and, consequently, to draw conclusions with respect to a variety of dislocation mechanisms for the deformation.

First of all, we should take note of the fact that in the alloy being tested here deformation comes about as a result of slippage (Fig. 3), as opposed to twinning, as was the case [7] when nanosecond laser pulses were directed against steel or against alloys with a low packing defect energy. The literature contains no quantitative data regarding the packing defect energy for the alloy being studied here; however, our investigations into the defect structure show it to be rather high (~50 erg/cm^2), because the electron-microscope photographs reveal virtually no packing defects nor the presence of any "constrictions" in the electron microdiffraction patterns. A second indirect confirmation is afforded by the formation of a cellular dislocation structure at greater levels of deformation.

We can see from Fig. 3 that the deformation comes about as a result of a single slippage system (primary for the given orientation of the monocrystalline specimen), with the slippage lines not uniformly distributed over the volume of the specimen, the majority of these lines being combined into slippage bundles. A consequence of this nonuniform distribution of the regions of plastic deformation over the volume of the specimen is the formation of inclined boundaries between neighboring blocks. An estimate of the rotation based on the data from the microdiffraction patterns shows that it is not overly large (~0.07 + 0.1°). A more detailed electron microscope study showed that dislocation is primarily concentrated in the interlayers of the matrix or in the two-phase ($\gamma + \gamma'$) regions with minute (30-50 nm) particles. However, in the case of large particles (250-500 nm) the dislocation density is small and individual dislocations are easily distinguished (Fig. 4). Dark-field image photography of these particles with reflex photography equipment and their analysis in accordance with the $(\bar{g} \times \bar{b})$ contrast rule confirmed that the majority of these dislocations are of the mixed type.

The above-described dislocation patterns reflect a structure that is formed in the surface layer of the specimen. With an increase in the depth of the layer, the amplitude of the shock wave becomes attenuated, and the level of deformation, and this means the density of defects, is reduced. In foil cut out of the laser-treatment zone, even to a depth of 1.5 mm, the effect of the shock wave remains quite strong. The change in the structure of the alloy due to the elastic action of the shock wave is perceptible even at this depth: at the boundaries separation the large γ' particles from the matrix we observe a significant quantity of uncoordinated dislocations (Fig. 5).

In those specimens for which the amplitude of the shock wave reaches $2\cdot10^3$ bar during the process of laser treatment, the magnitude of the plastic deformation is significantly greater than in the case of a shock wave with an amplitude of 10^3 bar. This is borne out not only by the higher defect density, but also by the participation of secondary slippage systems in the deformation (Fig. 6a), and furthermore by the fact that the dislocations move not only over the interlayers of the matrix, but through the large particles of the γ'-phase (Fig. 6b). It is characteristic that in the large particles of the γ'-phase, with an ordered structure, deformation comes about as a result of the movement of paired superdislocations analogous to the situation that is observed in deformation under conditions of uniaxial tension.

Yet another characteristic feature of the deformation of these specimens, subjected to the action of a shock wave with an amplitude of $2\cdot10^3$ bar, is the more substantial rotation (in comparison to the earlier-described pattern) of the adjacent blocks, reaching approximately 1°.

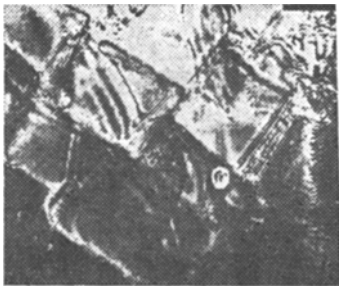

Fig. 5

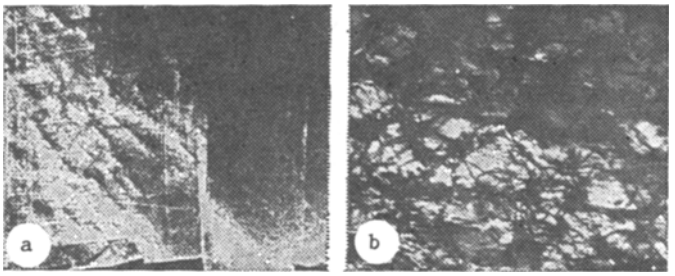

Fig. 6

Fig. 5. Electron-microscope image of noncoordination dislocation at the γ/γ' boundary of separation, dark field in reflex 220. × 37,000.

Fig. 6. Electron-microscope images of defect structure generated by the action of a shock wave with an amplitude of $2 \cdot 10^3$ bar: a) slippage bands of two systems, light field (× 10,000); b) dislocation structure, light field (× 30,000).

Thus, analysis of the dislocation structures formed in the alloy KhN57KVYu under shock waves generated by nanosecond laser pulses allows us to draw the conclusion that the mechanisms of plastic deformation are analogous to those which occur in the case of uniaxial tensile or compression strains. The plastic deformation caused by the shock wave and the increase in defect density must naturally lead to strain hardening of the alloy. The microhardness measurements at the specimen surfaces prior to the application of the laser pulses and subsequent to the laser load demonstrated that hardening as a result of laser treatment reaches to 20-25%.

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