Formation of intermetallic compounds in a niobium-iron system due to the action of a shock wave produced by laser irradiation

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(Submitted 16 December 1980)

Pis'ma Zh. Eksp. Teor. Fiz. **33**, No. 2, 126–129 (20 January 1981).

A nonequilibrium density of point defects, which are generated in a niobium-iron system due to the action of a shock wave produced by pulsed laser irradiation, resulted in the formation of intermetallic compounds which were identified by the Mössbauer spectroscopy method.

PACS numbers: 81.20.Gx, 79.20.Ds, 76.80. + y, 62.50. + p

Pulsed laser stimulation, which generates point defects in a solid, can alter significantly the properties of the irradiated material. The increase of T_c, as a result of formation of point defects due to passage of shock waves through the irradiated sample remained stable when superconducting materials were irradiated by a laser.[1]

The diffusion of defects from the volume of the sample to its surface and their nonequilibrium can alter significantly the chemical activity of the surface, which causes nonequilibrium chemical processes in the surface layer.

We report in this paper the first observation of the formation of intermetallic compounds when shock waves, which are caused by pulsed laser irradiation of the sample, pass through a massive metallic sample.

We have investigated the niobium-iron system. Since it was observed[2] during irradiation of a Nb surface (with an Fe^{57} layer deposited on it) by laser pulses with a duration of $\sim 10^{-3}$ sec that Fe atoms enter into the niobium matrix because of the thermal stimulus and form the hexagonal $NbFe_2$ structure, measures were taken to exclude possible thermal effects. The sample surface, opposite to that on which the iron layer was deposited, was subjected to laser irradiation. The duration of the irra-

diation pulse was chosen to be 2.5×10^{-8} sec. According to Ref. 3, the heating of niobium to a temperature amounting to 5% of the surface temperature penetrates to a depth of 1.5 μm during the time of the pulse. Consequently, the thermal action on the unirradiated surface is almost eliminated in samples with thickness greater than 10 μm. At the same time, according to Ref. 4, a stimulus duration of 2.5×10^{-8} sec and irradiation of metal with ruby-laser radiation can satisfy the condition for the formation of a shock wave at energies above 0.3 J; the elastic wave becomes a shock wave at a depth of 5 μm.

The samples were irradiated through a transparent condensed medium (distilled water) sequentially over the entire surface on the niobium side by the radiation of a ruby laser in the Q-switched mode of operation (the energy in a flash was 0.5 J, the flash duration was 2.5×10^{-8} sec, and the flash intensity was 2×10^{9} W/cm^2). The pressure at the front of a shock wave was equal to 3.3×10^{4} kgf/cm^2, according to Ref. 5. A copper plate with a conical, water-filled extension was placed on the sample to improve the uniformity of the stimulus, to eliminate plastic deformation of the sample, to amplify the pressure of the shock wave, and to obtain a given shape of the irradiated region. The irradiation was performed at room temperature. The experimental setup is shown in Fig. 1.

Samples with a thickness of 25–26 μm were investigated. An Fe film with a thickness of 6000 ± 250 Å was deposited on the niobium substrate by thermal evaporation in a vacuum of 2×10^{-8} mm Hg. A Mössbauer spectroscopic method was used to analyze the results of the stimulus, just as in Ref. 2.

The Mössbauer spectra were examined using a YaGRS-4 resonance spectrometer with a Co^{57} source in a chromium matrix. The source and the absorber were held at room temperature during the measurements.

Figure 2 shows the internal lines corresponding to transitions between the magnetic sublevels $+\frac{1}{2}\rightarrow-\frac{1}{2}$ and $-\frac{1}{2}\rightarrow+\frac{1}{2}$ of the sample before irradiation (A) and after irradiation (B). A weak-intensity paramagnetic line with an isomeric shift $\delta E=\pm0.06+0.02$ mm/sec is observed in the center of the spectrum of the irradiat-

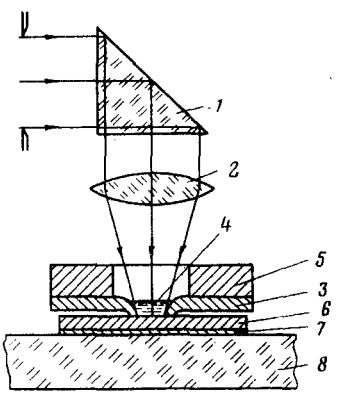

FIG. 1. Experimental setup. 1, Glass prism; 2, focusing lens; 3, copper plate; 4, transparent condensed medium (water); 5, clamping ring; 6, niobium foil; 7, iron layer; 8, substrate.

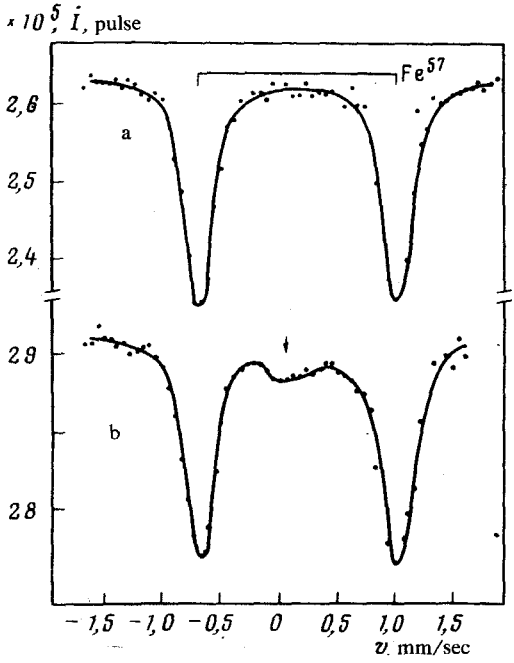

FIG. 2. Mössbauer spectrum of the sample (a) before laser irradiation and (b) after it.

ed sample. The ratio of the area of the paramagnetic peak to the area under the curve of the original Fe^{57} deposited on the niobium is about 2%.

The shape of the spectrum indicates that the Fe and Nb atoms are redistributed near the original interface and, after penetration , they form the intermetallic compounds $NbFe_2$ and NbFe.[2] The $NbFe_2$ compound, which has the structure of the variable-composition Laves phase[6] with a homogeneity region of 58–78% Fe, is normally formed at a temperature of 1770 °C.[7]

The NbFe phase with a homogeneity region of 50–54 at.% Fe apparently can also be formed as a result of irradiation. This phase is analogous to the $NbFe_2$ compound in structure and in interatomic distances, whose Mössbauer spectra are almost the same at room temperature. The average thickness of the layer of these intermetallic compounds, which was estimated from the ratio of the areas of the hyperfine (Fe^{57}) and unsplit components of the spectrum, is equal to about 100 Å.

The asymmetry of the paramagnetic line, because of the bulge on the right-hand side, is attributed to the superposition of the line of the solid solution of Fe in Nb with FeO oxide.[2]

To form a 100-Å diffusive layer of $NbFe_2$, the density of vacancies in the Nb foil must be equal to 0.6 at.%. i. e., it must be greater than their equilibrium concentration at the melting point.

Therefore, the high nonequilibrium concentration of point defects by means of a

laser shock-wave stimulus, their flow to the free surface of a metallic sample, and the counterdiffusion of adsorbed impurity atoms from the surface into the volume result in the formation of intermetallic compounds in the surface layer.

The laser generation of point defects can be regarded as a method of initiating chemical reactions in solids—laser solid-state chemistry.

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Translated by Eugene R. Heath
Edited by S. J. Amoretty