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Enhanced densification of porous nickel aluminide under shock compression

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Using a laser velocity interferometer, wave profiles were recorded in porous (porosity 30%) nickel aluminide samples. Data on shock compressibility were obtained. An abnormally high compaction was found, manifested in the intersection of Hugoniots of solid and porous samples at a pressure of 28 GPa, which indicates a phase transition.

Keywords: shock waves, Hugoniot, phase transitions, laser Doppler interferometers, intermetallides.

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Nickel aluminide (NiAl) is an intermetallide known for its unique high–temperature mechanical properties [1]. Due to its simple crystal structure, highly ordered lattice, wide homogeneity range in the phase diagram, and other properties, NiAl is also of great interest for fundamental research [2].

Studies of NiAl under dynamic loading were started in 1990s; they were evidently motivated by the necessity of getting ideas about strength characteristics of this high–temperature material promising for aircraft engine building [3]. The first fundamental study of the NiAl dynamic compressibility was [3]. As the samples, monocrystalline NiAl was used. The samples loading was performed by using Split-Hopkinson pressure bar. The loading amplitude did not exceed 2.5 GPa. In experiments of [4], the maximum pressure was 8 GPa. In [5], the polycrystalline NiAl loading amplitude reached 83 GPa. Those studies did not revealed any distinctive features of the NiAl behavior, except for the loss of elasticity near 1 GPa [3,5].

The above–mentioned studies were performed on monocrystalline and solid polycrystalline samples. At the same time, experiments on porous NiAl samples were of no less interest. Along with this, the use of porous samples makes it possible to essentially extend the temperature range in the shock–wave experiment [6]. This will enable analysis of the NiAl response to shock loading in a wider temperature range.

In this work, shock compressibility of NiAl samples with porosity of 30% was studied experimentally. Pellet–shaped samples 20 mm in diameter and 2–3 mm in thickness were fabricated by pressing the NiAl powder at a pressure of 6.4 t/cm^2 with subsequent sintering for an hour in vacuum ($1 \cdot 10^{-4}$ mm Hg) at the temperature of 1200–1250°C. The sample density was 4.16 ± 0.07 g/cm^3, which corresponds to the porosity of 29 ± 1%. The procedure for the NiAl powder preparation and certification is described in [5].

High pressure was created in the samples by using explosive throwing devices (Fig. 1).

Products of the explosive charge detonation accelerated the aluminum flyer *1* that reached the desired speed at the preset distance. The flyer collided with the aluminum screen *2* and generated a shock wave in the sample *4* glued on the opposite side of the screen. The moment of the shock wave entering the sample was detected by using a thin polarization gauge *3* mounted on the screen beneath the sample. The shock wave propagated through the sample and reached its interface with the water window or vacuum *6*. The interface began moving together with the titanium or aluminum foil *5* glued to the sample surface; its velocity was measured by laser interferometer VISAR (velocity interferometer system for any reflector) [7]. The loading parameters were varied by varying the explosive charge mass and flyer thickness.

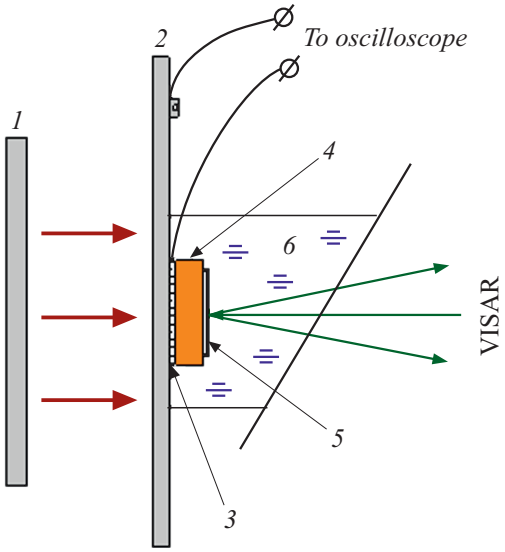

Figure 1. Experimental assembly. *1* — Al flyer, *2* — Al screen, *3* — polarization gauge detecting the shock wave entering from the screen into the sample, *4* — NiAl sample, *5* — Al or Ti foil, *6* — water window or air.

Parameters of experimental assemblies with increasing sample–loading pressure

Experiment No.	Flyer speed, km/s	Al flyer thickness, mm	Screen material (thickness)	Sample thickness, mm	Sample density, g/cm^3	Foil material (thickness)	Window
410	3.3	5	Cu (2 mm)	3.02	4.10	Al (0.01 mm)	Water
411	3.3	5	Cu (2 mm)	3.01	4.14	Al (0.01 mm)	≪
406	3.3	5	Al (4 mm)	3.03	4.10	Ti (0.20 mm)	Air
413	3.3	5	Al (4 mm)	3.02	4.13	Al (0.01 mm)	Water
305	4.6	2	Al (2 mm)	3.16	4.13	Al (0.01 mm)	≪
401	4.6	2	Al (2 mm)	1.90	4.13	Ti (0.20 mm)	Air

Parameters of the experimental assemblies are listed in the Table.

Hugoniots of the samples were determined by the „bracking“technique [7]. To determine the time of the shock wave propagation through the sample, time markers were used, namely, spikes on the polarization gauge signals and VISAR oscillograms. Processing of the VISAR oscillograms provided velocity profiles of the moving sample–water window interface.

Recording of the velocity profiles with the laser interferometer at the porous sample interface with a transparent medium is hindered by the formation of cumulative microjets that reduce reflectivity of the thin foil glued on the sample. Since selection of the foil thickness and material is a sophisticated problem, not all the experiments succeeded in recording velocity profiles of satisfactory quality.

Fig. 2 presents a velocity profile for the sample–water window interface (solid line) recorded in experiment № 413 (see the Table) under the shock compression pressure of 30 GPa.

The profile represented by the dashed line was recorded in the experiment without a sample when the laser beam was reflected directly from the screen–water interface. This profile provides an idea about the shape of a pulse entering the sample from the screen. Each velocity profile exhibits a shock spike, region of constant velocity, and decrease induced by the release wave coming from the flyer back side. The distance between shock spikes shown in the figure matches with the time of the shock wave propagation through the sample.

Fig. 3 presents Hugoniots of the solid [5] and porous (this paper) NiAl in the $P-V$ coordinates.

As Fig. 3 shows, the porous NiAl Hugoniot intersects that for solid NiAl at the pressure of 28 GPa. It is evident that such an intersection is impossible if the substance has not undergone any changes in the structure or composition, since porous materials get heated stronger in the shock wave, and their Hugoniots are expected to pass higher than those of solid matters. Such an unusual behavior may be explained by a phase transition or, e. g., decomposition of NiAl. However, NiAl formation from Al and Ni proceeds with a decrease in volume and, hence, high pressure cannot promote the compound decomposition into Al and Ni. The NiAl decomposition with formation of other nickel aluminides is also hardly likely since, as shown by the Ni–Al system phase diagram, these substances are less stable than NiAl. Therefore, the occurrence of phase transformation is most probable. The upper–bound estimate of the degree of compaction during the phase transition, which was obtained

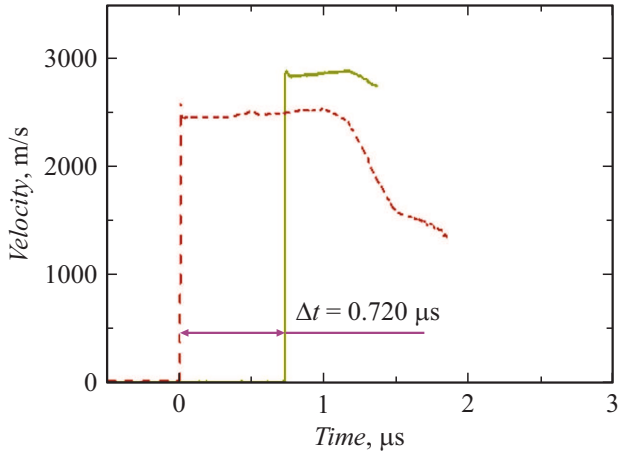

Figure 2. Particle velocity profile at the sample–water window interface in experiment № 413 (solid line).

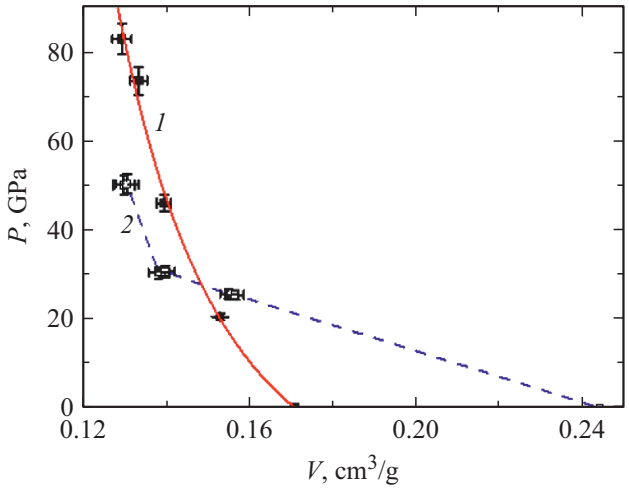

Figure 3. NiAl Hugoniots in the $P-V$ coordinates. *1* — solid samples [5], *2* — porous samples.

by extrapolating the upper part of the porous NiAl Hugoniot to the zero pressure, shows that this degree is sufficiently high and equals about 10%.

Similar Hugoniot intersections were observed earlier in experiments with silicon dioxide, boron carbide, uranium dioxide, and tantalum pentoxide [8]. We have revealed this phenomenon in [9] for the case of shock compression of porous β-Si_3N_4 samples. This was explained by reduction of the threshold pressure of transition to supersolid phase γ-Si_3N_4 because of a higher shock compression temperature of porous samples. Based on calculations, papers [10,11] predicted for silicon an enhanced densification at shock compression taking place during transition to the β-Sn structure or nearly similar orthorhombic modification. Those papers established that the decisive role in arising of the enhanced densification is played by the shear strain near the pore walls, while heating is considerably lower than in the case of shock compression of an inert porous substance.

Along with studying the shock compressibility, of great interest is establishment of the structure of the high−pressure NiAl phase manifested by an enhanced densification of porous samples, as well as the possibility of its retention. Later we are going to perform experiments at shock compression in recovery ampoules and also to obtain the porous NiAl Hugoniot points at pressures below 20 GPa and above 50 GPa.

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Conflict of interests

The authors declare that they have no conflict of interests.

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