STUDY OF MECHANICAL CHARACTERISTICS UNDER THE CONDITIONS OF SHOCKWAVE DEFORMATION OF AL-$AL_2 0_3$ COMPOSITES PRODUCED BY MEANS OF SHOCKWAVE COMPACTION

I. Zhukov[1], G. Garkushin[1,2], S.Vorozhtsov[1],
S.Razorenov[1,2], A.Vorozhtsov[1], V. Promakhov[1], A. Zhukov[1]
[1] National Research Tomsk State University, Russia
[2]Institute of Problems of Chemical Physics of Russian Academy of Sciences

Particle-reinforced composites can be produced using solid-phase methods of powder metallurgy and liquid-phase casting methods. Al-matrix composites with Al_2O_3 reinforcing particles are well known. Such composites are usually produced by means of solid-phase sintering of powders. However such method does not make it possible to produce nanoparticle-reinforced composites as in the process of sintering nano-particles become micro-particles due to diffusion processes. Shockwave compaction is one of the methods providing quick impact of pressure and temperature on powder mixture. This method make it possible achieve high density of products while maintaining initial particle size [1,2]. Structure and mechanical properties of such composites under static loads are well studied in [3-5]. The study of mechanical characteristics of Al - Al_2O_3 composites in a wide range of deformation velocities from $10^{-5}c^{-1}$ to $10^{5}c^{-1}$ is of specific interest because it can help to determine mechanisms of deformation, fracture as well as their connection with internal microstructure of composites, formed in the process of shockwave compaction of powder mixtures. It should be noted that high-speed deformation and fracture processes caused by a shockwave in such materials are not studied at all. Thus, *the objective of this work* is to study the influence of structure and properties of Al-10%Al_2O_3 composites produced by means of shockwave compaction of powder mixtures on resistance to high-speed deformation and fracture under the conditions of impact compression.

In the framework of this study samples of composite materials were synthesized from Al powder mixtures (average particle size 5-6 μm) and 10% alumina (average particle size 36 nm) using the method of shockwave compaction. "Uglenit E6" industrial explosive compacted up to ρ=1.25 g/cm3 was used as explosive. Estimated compression pressure comprised 13 – 15GPa. Initial structure of powders and obtained composite materials was performed using electron microscopy. Crystal structure parameters as well as phase composition of initial powders and obtained composites were studied using an X-ray diffractometer Shimadzu with filtered CuKα radiation. Specific surface area of powders was measures using the method of low-temperature nitrogen adsorption.

SEM-image of Al powder in its initial state is shown in Figure 1 the porder is then used for synthesis of composite. As it can be seen, Al powder consists of particles with a regular spherical form. Measured average particle size comprised 5-6 μm (largest particles ~18 μm). Specific surface area of the powder comprised 0.7 m^2/g. XRD analysis of the powder indicated that the size of crystallites (coherent scattering regions (CSR)) comprises 110 nm with crystal lattice parameter of 4.0479 Å and crystal lattice microdistortion $<\varepsilon^2>^{1/2}$ $2.9*10^{-3}$.

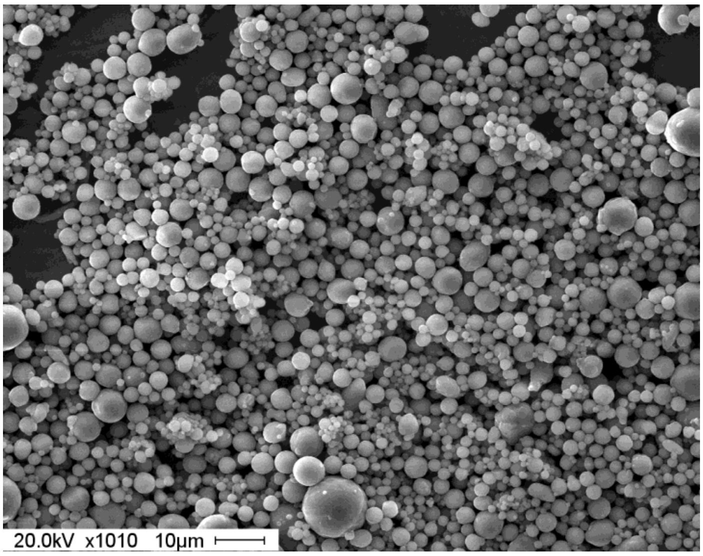


Figure 1 – SEM image of Al powder

SEM images of Al_2O_3 powder produced by means of EEW method are shown in Figure 2. As it can be seen, powder particles are not agglomerated and have a regular spherical form. XRD analysis indicated that Al_2O_3 powder consists mainly of α-Al_2O_3 phase, however, there are traces of γ-modifications. Specific surface area of the powder comprises 35 – 40 m^2/g. Average particle size comprises $\tilde{a}_n$ = 36 nm; surface average size $\tilde{a}_s$ = 45 nm; mass-average size $\tilde{a}_m$ = 54 nm.

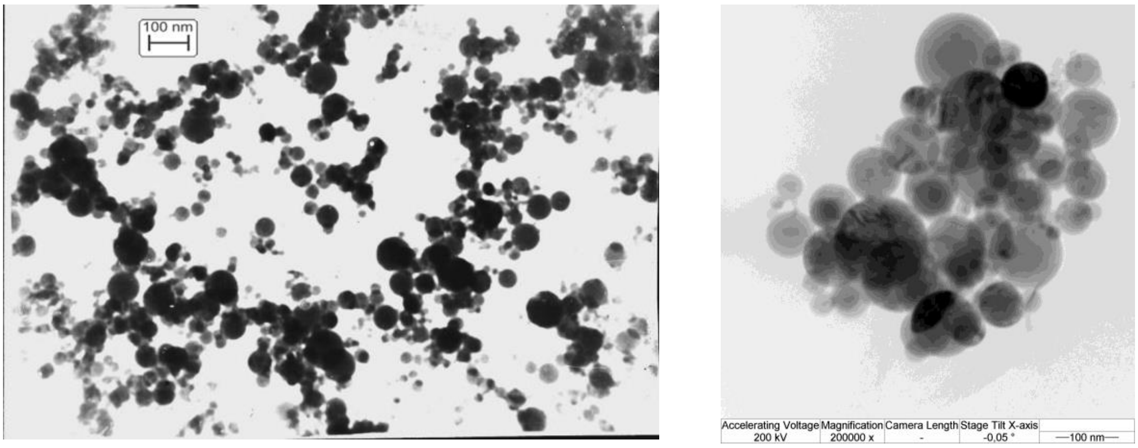
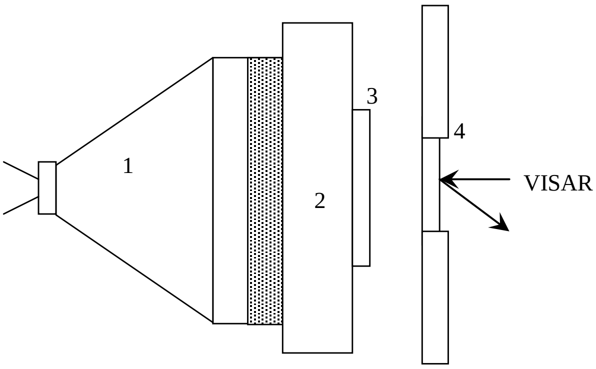


Figure 2 – TEM image of Al_2O_3 powder

Average grain size for synthesized composites comprised approximately 9 μm. According to XRD analysis data obtained composites contained 89.5 % of Al phase and 10,5 % of α-Al_2O_3 phase. Al lattice parameter for obtained composites comprised a=0.40483 nm, crystal lattice microdistortion $<\varepsilon^2>^{1/2}$ $0.6*10^{-3}$, Al phase CSR size comprised 65 nm.

Density of obtained composites was measured using the method of hydrostatic weighing and comprised 2.65±0.01 g/cm^3. It is known that the density of commercially pure Al comprises 2.7 g/cm^3. Porosity of the compact comprised 2%. Vickers microhardness tests were performed using NHT-TTX table top nanoindentation tester with maximum load of 100 mN, maximum indentation depth of 2100nm and loading rate of 200 mN/min, loading time comprised 15 s. Average value of microhardness comprised 106±6 kg/mm^2. The values of longitudinal sound velocity c_L were obtained using an instrument for measurement of acoustic waves in solid bodies and penetrating sonic testing method and comprised 6.10±0.1 km/s. The spread of velocity values ±0.1 km/s is possibly explained by inhomogeneity of the structure (porosity, microfractures) formed in the process of shockwave compaction of powder mixture. Compression tests of composites were performed using Instron equipment. Ultimate compressive strength comprised 450 MPa. Further studies of elastic-plastic and strength characteristics were performed for samples under the conditions of shockwave tests [6].

Shockwave compaction tests were performed for composite samples with the thickness of 2mm and 5 mm. Plane shock waves in composite samples were generated by striker plates with the thickness of 0.85 mm and 2 mm respectively, accelerated to the speed of 630±30 m/s by means of special plane shockwave generators [6]. AD1 (commercially pure aluminum reinforced by pressure only) was selected as a material for striker plates. Schematic diagram and a photo of experimental unit used for composite loading under the conditions of conditions of impact compression are shown in Figure 3. Plane shockwave generators provide required loading conditions and high degree of homogeneity of deformation of studied samples which is achieved by means of mutual collision of two plane-parallel plates. Collision induces a shockwave in the sample, after a shockwave a constant state is maintained for the time period of wave circulation in the striker plate. The study is based on the fact that processes of elastic-plastic deformation and fracture are associated with the change of material compressibility and manifest themselves in the structure of intensive waves of compression and rarefaction. Interference between incident and reflected rarefaction waves leads to tension inside the body which initiates a high-speed fracture – spallation. In the process of loading of studied samples continuous registration of movement of their free back surface was performed using Doppler velocity interferometer VISAR (Velocity Interferometer System for Any Reflection) [7]. Free surface velocity profiles $u_{fs}(t)$ were recorded with the resolution of 1ns (time) and ±3 m/s (velocity).



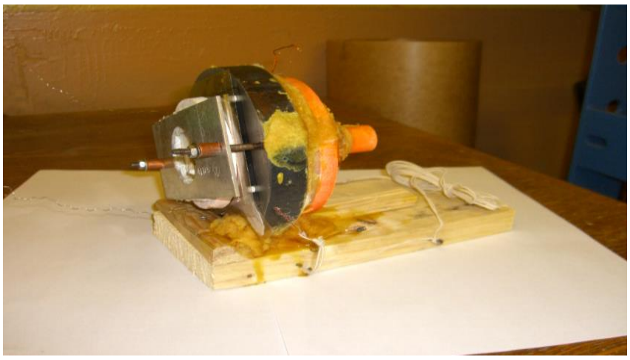


Figure 3 – Schematic diagram of experimental unit used for composite loading: 1 – explosive lens (AIX-1), 2 – steel attenuator plate (thickness 20 mm), 3 – aluminum striker plate (0.85 mm or 2 mm), 4 –synthesized composite material sample.

Obtained oscillograms are processed using a special-purpose PC software developed in the Physical gas dynamics laboratory of IPCP RAS by V.K.Gryaznov. Computer processing makes it possible to determine values of velocity of moving surface at any moment of time with the error of ±5 m/s regardless of absolute value of surface velocity.

Experimental profiles of free surface velocity of studied composite samples in comparison with the profile for commercially pure Al alloy AD1 are shown in Figure 4.

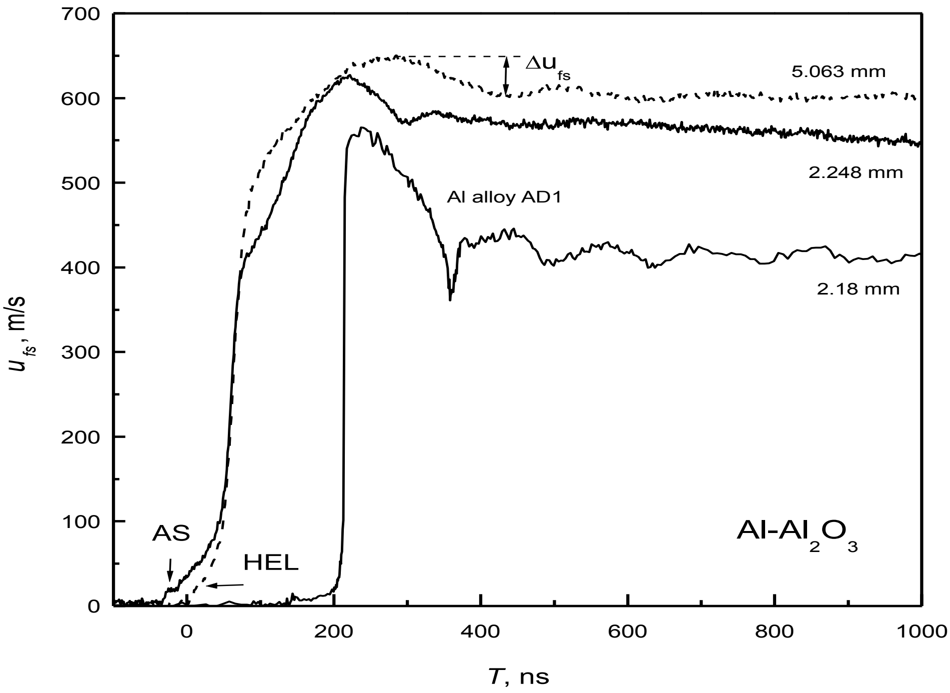


Figure 4 – Profiles of free surface velocity of studied composites in comparison with the profile for commercially pure Al alloy AD1.

Coming out of elastic plastic compression wave to the surface and subsequent rarefaction wave are registered on wave profiles. Weak compression wave previous to the front of elastic precursor (marked as AS in Fig. 4) is a result of the impact of air shockwave in front flying striker plate. The period of increase of parameters in plastic shockwave is determined by material viscosity or stress relaxation period. Loading conditions near free back surface of the sample correspond to the beginning of shockwave attenuation under the impact of a catching up rarefaction wave for given ratio of striker plate and sample thicknesses. After reflection of compression pulse from the free surface tensile stresses are generated inside the sample, initiating its fracture – spallation. Here relaxation of tensile stresses takes place and compression wave is formed (spallation pulse) which comes to sample surface causing a second increase of its(wave) velocity. Subsequent damped oscillations of velocity are associated with reverberation of spallation pulse in spallation plate separated from the sample.

Uniaxial compressive stress after the front of elastic precursor HEL Fig. 4, equal to material dynamic yield strength is calculated using the following formula [6]:

$$\sigma_{HEL} = \rho_0 c_l u_{fs}^{HEL} / 2, \quad (1)$$

where ρ_0 – alloy density, c_l, – longitudinal sound velocity, u_{fs}^{HEL} – the value of free surface velocity after the front of elastic precursor. Surface velocity decrement Δu_{fs} (Fig. 4) during its decrease from maximum value to the value prior to the spallation pulse front is proportional to the value of fracture stress – spallation strength of material under given loading conditions. In linear (acoustic) approximation its value is equal to:

$$\sigma_{sp} = \frac{1}{2} \rho_0 c_b (\Delta u_{fs} + \delta u), \quad (2)$$

where c_b –volume velocity of sound, δu – correction for velocity profile distortion due to difference between the velocity of a spallation pulse front and the velocity of plastic part of an incident unloading wave in front of it[8]. Such distortions take place when relaxation of stresses in the process of fracture generates a compression wave in the stretched material, the front of this wave represents an elastic wave catching up an unloading part of incident compression pulse and having the volume velocity of sound (c_b).

As it was expected, an increase of dynamic yield strength was registered for synthesized composites which can be attributed to introduction of Al_2O_3 particles. Measured values of dynamic yield strength of composite materials for samples with the thickness of 2mm and 5mm comprised 0.24±0.01GPa and 0.2±0.01GPa respectively, the value for pure Al comprised 0.12±0.02GPa (sample thickness 2.13mm). Composite dynamic strength comprised 0.4GPa and 0.35GPa for samples with the thickness of 2mm and 5mm respectively, the value for commercially pure Al alloy comprised 1.8GPa (sample thickness 2.13 mm). It is known that fracture of solid bodies takes place by means of nucleation, growth and coalescence of microdiscontinuities under the influence of tensile stresses. Defects of various levels in metals become nucleation centers. Observed decrease of strength in Al - Al_2O_3 composites is associated with the fact that there is a significant increase of microdefects (~2% porosity in particular) associated with the passing of a strong shockwave through the sample. It is not possible to produce absolutely dense and defectless compacts using shockwave compaction method. Relatively large defects such as micro-pores and grain boundaries (powder boundaries) require less strain to convert them into fracture centers. As fracture centers grow and coalesce the resistance to further fracture decreases. High strength of pure homogenized Al is explained by the absence of potential fracture centers in the structure i.e. added Al_2O_3 particles and residual porosity. Summarized experimental parameters for composite material samples and calculated values of elastic plastic and strength characteristics are given in Table 1.

Table 1

№	h_{sam}, mm	h_{imp}, mm	u_{HEL}, m/s	σ_{HEL}, GPa	Δu_{fs}, м/с	σ_{sp}, ГПа	hsp мм	P_{max}, ГПа	$\dot{V}/V_0$, c^{-1}
1	5.06	2.01	28	0.20	44	0.37	0.90	4.9	2.8×10^4
2	2.25	0.85	36	0.24	53	0.45	0.62	4.7	8.8×10^4
AD1	2.18	0.40	14	0.12	206	1.8	0.41	4.4	6.3×10^5

where № - test number, h_{sam} – sample thickness, h_{imp} – striker thickness, h_{sp} – spallation plate thickness, P_{max} – maximum impact compression pressure $\dot{V}/V_0$ – pre-fracture sample deformation velocity.

Thus, performed shockwave experiments using VISAR laser interferometer have indicated that additional introduction of 10% alumina into Al matrix can improve dynamic yield strength in comparison with commercially pure Al alloy AD1.

It was found that there is residual porosity of ~2%, in composites synthesized by means of shockwave powder compaction, this residual porosity and most likely insufficient strength at powder boundaries after shockwave compaction significantly reduces fracture strength.

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