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LIGHT-METAL MATRIX (NANO)-COMPOSITES

Emerging Processes

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THE PHYSICAL-MECHANICAL PROPERTIES OF ALUMINUM NANOCOMPOSITES PRODUCED BY HIGH ENERGY EXPLOSION IMPACT

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Abstract

The present paper uses explosion compacting of Al nanoparticles to create light nanocomposite with increased physico-mechanical properties. Russian civil explosive Uglenit was chosen as high energy material for compacting. The formation of the structure and properties of aluminum based materials after shock-wave impact was studied. It was found that shock-wave treatment of different samples a) aluminum powder and b) powder mixtures Al +10 wt.% C (in the form of detonation diamonds) and c) Al +10 wt.% Al_2O_3 produces nanostructed materials with almost the theoretical density. X-ray diffraction analysis showed that in the samples with the addition of carbon and aluminum oxide was formed two-phase state of aluminum with a significantly different structure parameters. In this case, the lattice parameter of nanophase increased by 0.5%, which testifies to its non-equilibrium state. This increase of the parameter may be due to compressive stress, evaluation of which gives the value of 350 MPa. It was shown that the materials have high values of mechanical properties - hardness, compressive yield strength.

Introduction

It is known [1], that material properties are strongly influenced by its internal structure - presence of defects, size of structural elements, presence of reinforcing elements etc. if is not always possible to form desired structure using traditional production schemes. Particularly traditional metallurgical processes are associated with an increase of grain size and defect annealing, which require additional mechanical processing of the material. The method of dynamic powder compaction enables manufacturing of a broad variety of solidity material with desired composition and density close to theoretical value; additionally this processing technique facilitates introduction of desired number of defects and reinforcement elements.

Such technologies are extremely important for production of Al composites by means of high energy explosion impact (shock-wave (SW) treatment) [1] on powder aluminum alloys with necessary content of aluminum oxide as a surface film, which acts as a source of aluminum oxide reinforcement particles after shock loading. At the same time this method of aluminum powder treatment facilitates to change the type and quantity of reinforcement material, e.g. aluminum oxide nanoparticles, high-modulus carbon particles in the form of nanodiamonds etc. This method enables processing of materials with desired properties.

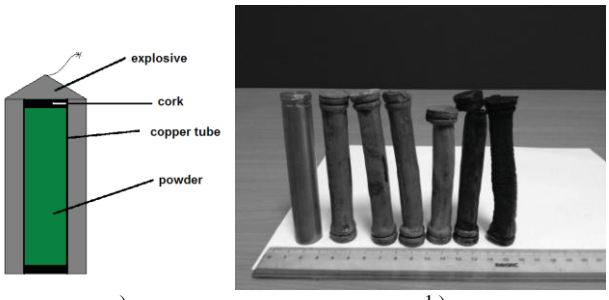
A major challenge with aluminum-base materials, the most frequently used structural materials of current interest, is to improve their mechanical properties (elastic modulus, yield strength, and hardness) by introducing high-strength nanocrystalline particles [2].

The objective of this work is to study properties of nanocomposites produced by high energy explosion impact of aluminum powder mixed with aluminum oxide nanoparticles and nanodiamonds.

Materials and Method

The materials to be investigated were nanopowders of aluminum produced by electrical explosion of wires [3], carbon in the form of detonation diamonds [4], produced by detonation method and aluminum oxide, obtained by plasma-chemical method [5]. The alumina and carbon content was 10wt.%. The composites were produced by shock-wave treatment [1, 6]. A 30mm layer of explosive (pad) compacted to ρ=1,25 g/cm^3 was poured into a cardboard glass (Ø=40 mm).

Used of a standard commercial explosive Uglenit E-6 (0.453 of TNT equivalent) exhibiting fugacity of 130 cm3 and velocity of detonation D = 2100–2500 m/s [7]. A tube was installed onto the pad using a centering cardboard ring. The gap was also fitted with compacted explosive. A copper tube with powder mixture of designated composition was centered by means of the second ring, and then compacted explosive was put into the glass 50mm above the tube. A standard electric detonator was installed In the middle of this layer at 20mm depth. Total mass of explosive was comprised 300g. The assembly was put into the blast chamber on a metal plate, detonator was connected to initiation grid, the chamber was dosed and the assembly was blasted. During detonation wave propagation, the pressure was P = 13–15 kBar. On the Fig. 1 shown the scheme for SW-treatment of copper tube with powder mixtures and the samples before and after SW-treatment.



a) b)

Figure 1. The scheme for SW-treatment of copper tube with powder mixtures (a) and the samples before (left) and after SW-treatment (b)

Phase composition and structural parameters of initial powders and obtained materials were studied using diffractometers with Cu$K\alpha$ - radiation. Step-by-step collection of X-ray patterns was performed with 0.02-0.1° step in the interval $20°<2\theta<120°$. Phase identification was performed by means of comparison of experimental pattern with ASTM-data. The sizes of crystallites were determined by using small-angle peaks and microdistortion of crystal lattice $<\varepsilon^2>^{1/2}$ was calculated using widening of reflection at large diffraction angles [8].

The structure of the composites was examined under a Philips SEM 515 microscope. The hardness of the materials was measured by a Super-Vickers hardness meter under a load of 1000g. Compression tests were performed using an Instron 1185 testing machine.

Results and Discussion

According to X-ray diffraction (XRD) analysis average crystallite size for Al powder comprised 90 nm, microdistorsion of crystal lattice – 10^{-3}. X-ray phase analysis has indicated that carbon powder consists of an X- ray amorphous phase (40%) and diamond phase (45%), the remaining part is represented by crystalline carbon. Average crystallite size for nanodiamonds comprises 4 nm, microdistorsion of crystal lattice – 17×10^{-3}. According to XRD analysis average crystallite size for alumina powder comprised 30 nm, microdistorsion of crystal lattice – 5×10^{-3}.

It is obvious from the grain size distributions shown in Fig. 2 that the average grain size in the material in the initial state is 220 μm and on exposure to shock waves on the Al powder, it reduces down to 10 μm. However, grains of size as large as 70 μm are also observed. An energy dispersive X-ray analysis (EDAX) analysis of the entire Al surface has revealed that besides aluminum, the material contains 15 at.% of oxygen due to the presence of an aluminum oxide film.

A metallographic analysis has disclosed that in the material Al–C grains with distinct faces and average size of 11 μm are present on the sample surface (Fig. 2*b*). Notably, the material contains 13 at.% of oxygen and 12 at.% of carbon. It is evident from the grain size distribution in Al–Al_2O_3 (Fig. 2*c*) that the average grain size has reduced down to 3.8 μm, whereas the amount of oxygen has increased to 25 at.%. Thus, metallographic examinations have indicated that shock-wave treatment of investigated mixtures makes it possible to achieve pore less condition (for example Fig. 3).

The grain size of SW-treated materials in this case comprises 4-20 μm depending on the type of mixture, which is significantly larger than powder particle size. This appears to be the result of dynamic recrystallization which took place during explosive treatment. In this case if grain size for the samples from aluminum nanopowder comprises 20±10 μm, introduction of reinforcement particles significantly reduces it down to 11 μm for nanodiamond-containing mixtures, and to 4 μm for mixtures which contain aluminum oxide.

Fig. 4 shows X-ray data, obtained for samples after SW-treatment of aluminum- nanocrystalline aluminum oxide mixtures.

Obtained data indicate that double-phase state with significantly different structural parameters was formed for samples containing nanodiamond and aluminum oxide. This state is indicated with an arrow on Fig. 4 - a small reflection near the main one, which belongs to aluminum.

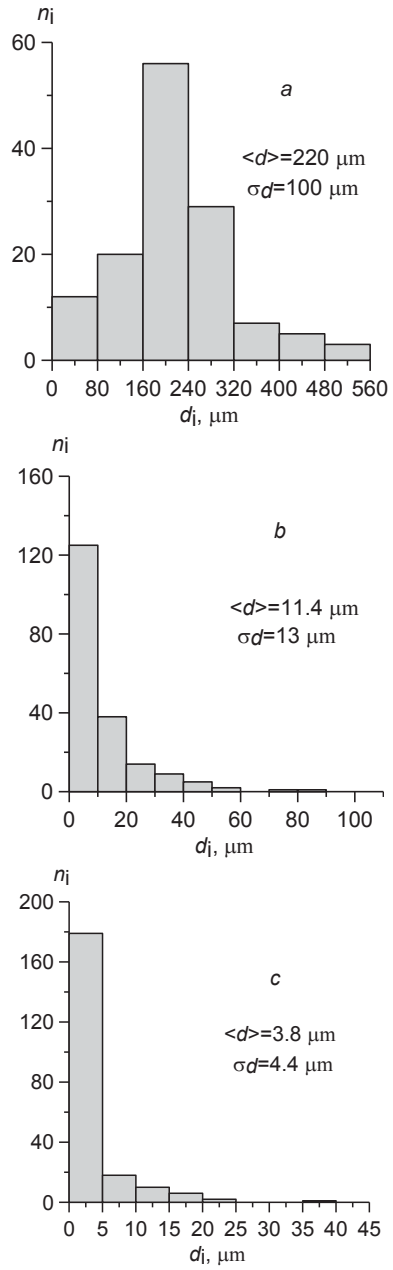


Figure 2. Grain size distribution in commercial 99.5 % pure aluminum (*a*), Al-C (*b*) and Al–Al_2O_3 (*c*) materials obtained by shock-wave treatment.

The study of parameters of fine crystalline structure have indicated that sizes of crystalline particles of main aluminum phase in all cases are equal to 80±10 nm, this value is close to the size of the crystallites in the powder of aluminum in the initial state.

Sizes of aluminum nanophase for SW-treatment mixtures with nanodiamonds are equal to 13±5 nm, while in case of aluminum oxide powder additions - they are equal to 8±5 nm. Lattice parameter of the nanophase is increased by 0.5% in this case, which indicates its non-equilibrium state. Such an increase may be associated with compressive residual stresses applied at the radius of compacted cylinder with powder mixture. Estimates have indicated that these stresses are equal to 350 MPa.

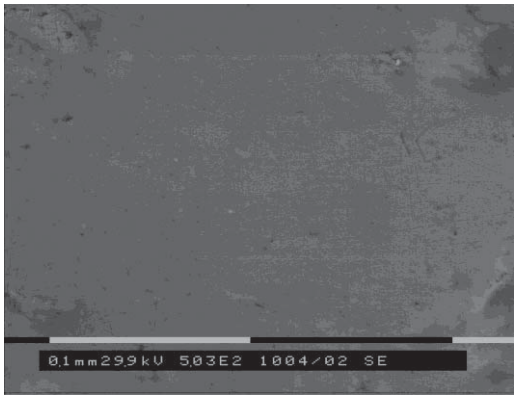


Figure 3. Microstructure of an composite produced by shock-wave treatment of an aluminum powder (the line size bars show the magnification).

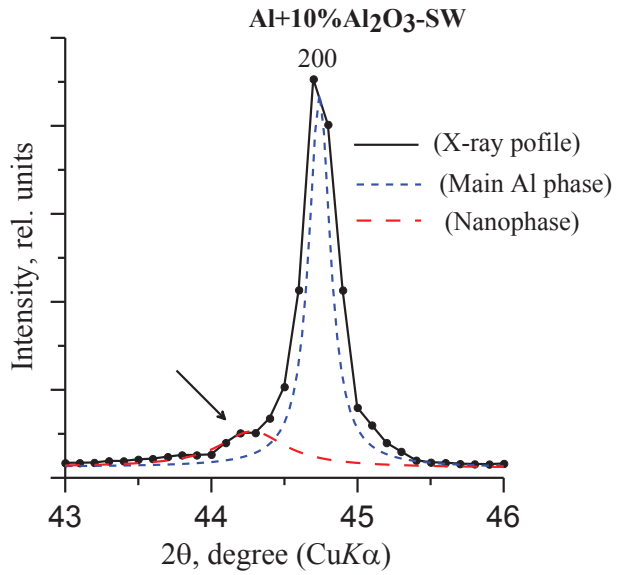


Figure 4. X-ray spectra of the Al–Al_2O_3 sample obtained by shock-wave treatment.

The fact that there are many residual stresses influences mechanical properties of SW-treated materials (see table I). Indeed, hardness measurements have indicated a 10-time increasing with maximum values for samples containing aluminum oxide, which is likely to be due to transformation of part of the bulk of the material to a nanocrystalline state, with the characteristic size of the structure elements being 10 nm. Furthermore, the yield strength and the value of plastic deformation of the materials obtained by SW-treatment significant increases.

The fact that these residual stresses are stipulated by shock-wave treatment is confirmed by the data obtained for hardness and strength characteristics after annealing (heating up to 500 ^{0}C with holding time 1 hour) of compacted samples given in brackets in the table I. As it can be seen there is a significant stress relaxation, however, it is less significant for samples with nanodiamonds.

Microdistorsion of crystal lattice (Table II) was determined using diffraction patterns for Williamson-Hall relationship. Microdistortion value has increased after adding hard particles.

These values match with estimates made for metal powders [9] and make it possible to estimate stored energy [10].

Table I. Mechanical characteristics of the test samples

Sample	Hardness, HV, MPa	Yield strength, MPa	Plastic deformation, ε_y
Al technical grade	190	30	0.0036
Al after SW-treatment	870 (35 after annealing)	-	-
Al+C after SW-treatment	1025 (190 after annealing)	400 (240 after annealing)	0.023 (0.014 after annealing)
Al+Al_2O_3 after SW-treatment	1360 (140 after annealing)	500 (225 after annealing)	0.0205 (0.0105 after annealing)

As it can be seen from the table this energy increases when high-modulus particles are added. A shock wave taking place in powder containing tube seems to spend its energy on Al activation as well as on activation of particles.

Assuming the simplest case of additive contribution to activation of Al particles by hard ones estimates of stored energy of alumina and nanodiamonds can be obtained. The value for alumina comprised 1.1 J/kg which corresponds to data mentioned in [10], as for nanodiamonds, the value was two times lower. This can be explained by complexity of phase composition of carbon mixture consisting of an X-ray amorphous phase, diamond phase and crystalline carbon. The data regarding the change of parameters of crystal lattice of investigated materials in the process of shock-wave treatment depending on stored energy are shown on Fig. 5.

Table II. The microstructural parameters of the test samples

Sample	Crystallite size of aluminum/ nanophase, nm	Micro-distortion of Al-lattice, $\langle\varepsilon^2\rangle^{1/2}$, 10^{-3}	Stored energy for aluminum, J/g
Al technical grade	155	-	-
Al after SW-treatment	70	0.75	0.042
Al+C after SW-treatment	90 /13	1.16	0.099
Al+Al_2O_3 after SW-treatment	70 /8	1.43	0.151

As it can be seen this relationship has a maximum peak, which can be explained on one hand by the growth of microstrains (microdeformation of crystal lattice) and on the other hand – by annealing of defects due to more intense heating of Al powder after adding hard particles in comparison with "pure" powder.

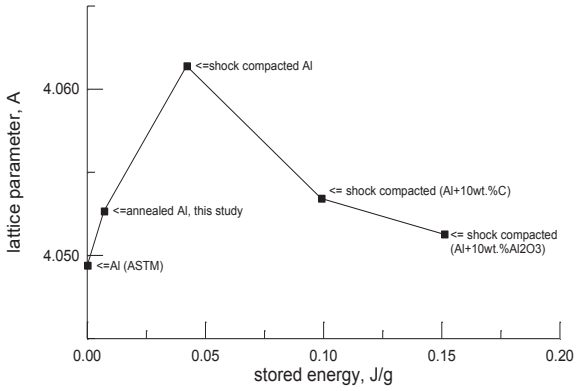


Figure 5. The change of parameters of crystal lattice of investigated materials in the process of shock-wave treatment depending on stored energy

Conclusion

It was shown that shock-wave treatment of aluminum powder mixtures Al+10wt.%C and Al+10 wt.% Al_2O_3 in copper capsules makes it possible to obtain materials with almost theoretical density and significantly better mechanical characteristics such as hardness and yield strength. The reason for this is that the part of material changes its state to nanostructured one with the size of structural elements equal approximately 10 nm and formation of compression stresses in a loaded samples up to 350 MPa.

Acknowledgements

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