The influence of the admixture of the fullerene C_{60} on the strength properties of aluminum and copper under shock-wave loading

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Abstract. Hugoniot elastic limit (HEL) and dynamic (spall) strength measurements of pressed aluminum and copper samples with an admixture of the fullerene C_{60} with 2-5 wt% under shock-wave loading were carried out. The peak pressure in the shock-wave was equal to 6 GPa. The measurements of the elastic-plastic and strength properties were based on the recording and the subsequent analysis of the sample free surface velocity histories, recorded by Velocity Interferometric System for Any Reflection (VISAR). It was found that the admixture of 5 wt% fullerene in aluminum samples led to an increase of the Hugoniot elastic limit for aluminum samples by a factor of ten. The copper samples with the admixture of 2 wt% fullerene also demonstrated an increase of the Hugoniot elastic limit in comparison with commercial copper. The measured values of the Hugoniot elastic limit were equal to 0.82-1.56 GPa for aluminum samples and 1.35-3.46 GPa for copper samples, depending on their porosity. As expected, the spall strength of the samples with fullerene decreased by about three times in comparison with the undoped samples as a result of the influence of the solid fullerene particles which were concentrators of tension stresses in the material under dynamic fracture.

1. Introduction

The mechanical properties of structural materials depend on their internal structure, the methods of their production, and their processing. One way to modify the properties of these materials is the use of different additives. For the last ten years investigations of the properties of materials with the fullerenes additive and their derivatives have been actively carried out. The use of the fullerenes as an additive to some materials can increase their strength; for example, the microhardness or the yield strength can increase several times [1]. Such unexpected strength behavior of aluminum and copper samples with the admixture of the fullerene C_{60} under static load conditions was a motivation to study the influence of fullerene additives on such properties as the Hugoniot elastic limit and the spall strength under shock wave loading as described this work.

2. Materials and experimental procedure

The tested materials were undoped pressed aluminum and copper samples and samples pressed from the mixture of Al or Cu powder with fullerene C_{60}. The content of fullerenes for the aluminum mixture samples was 5 wt% and for the copper mixture samples was 2 wt%. The undoped samples were pressed under a peak pressure of 5 kbar, while the samples with fullerene C_{60} were pressed under the pressures of 10 kbar or 7 kbar at temperatures of 280°C and 400 – 450°C for the aluminum and copper samples, respectively. For the preparation of aluminium and copper mixture samples we used aluminium powder with a particle size of 100 μm and 99.5% purity, copper powder with a particle size of 10 μm and 99.5% purity, and C_{60} with a particle size of 5-100 μm and 99.5 – 99.9% purity. The mixtures of aluminium or copper and fullerene powders were treated in a planetary mill to reach nanostructure state and then were sintered under high pressure and temperature [1,2]. The final structure of the samples modified by fullerenes was nanoclusters of Al-C_{60} or Cu-C_{60} agglomerated in strong particles with the size of 1-10 μm, which consisted in turn of crystallites with an average size of ~54 nm for Al-C_{60} samples or ~33 nm for Cu-C_{60} samples. The method of preparation of the mixed samples Al-C_{60} and Cu-C_{60} was described in more detail in [1, 2]. The sample preparation conditions are presented in table 1.

For all samples, density, sound speeds, and hardness were measured. The densities for the Al-C_{60} and Cu-C_{60} samples were equal to 2.6 g/cm^3 and 7.8 g/cm^3, and the sound velocities were equal to 5.4 km/s and 3.5 km/s, respectively. The microhardness of aluminum samples mixed with C_{60} have been shown to increase by a factor of 3-4 [1]. The admixture of the fullerene to the samples also led to the increase of their Vickers hardness to 3 times that of pure aluminum samples and to 1.3 times that of pure copper samples.

Table 1. The sample preparation conditions (pressures and temperatures).

	Al + 5% C_{60}	**Cu + 2% C_{60}**
Group 1	P_{press} = 10 kbar, T_{press} = 280°C	P_{press} = 5 – 7 kbar, T_{press} = 450°C
Group 2	P_{press} = 7 kbar, T_{press} = 280°C	P_{press} = 7 kbar, T_{press} = 400°C

Shock-wave loading of the sample with 2 mm thickness was created with a plane aluminum impactor of 0.4 mm in thickness accelerated by explosives to a velocity of 0.66 km/s [3]. As a result, a shock wave of maximum intensity approximately 6 GPa was generated in the sample by the impact of an aluminum flyer plate. In the experiments, the particle velocity histories were recorded with the laser Doppler velocimeter VISAR [4].

3. Experimental Results

Figure 1 presents the results of the experiments with the samples of undoped aluminum Al (profiles 1 and 4) and aluminium mixture Al + 5% C_{60} (profiles 2-3 and 5-6) pressed under 10 kbar (a) and 7 kbar (b). A weak (several m/s) precursor before the first shock front was caused by the air wave propagating in front of the impactor and was registered in all the particle velocity histories. Typical velocity histories for experiments with spall fracture were observed for the samples of pure aluminum in both cases (profiles 1 and 4). At first, the compression wave arrived on the surface of the sample, followed by the unloading wave propagating until the moment of spall fracture. The spall led to the formation of a distinct spall impulse causing the subsequent decaying velocity oscillations associated with reverberation in the spall plate. On the wave profiles 1 and 4, before the plastic wave a slight jump in velocity associated with the arrival at the sample surface of an elastic precursor with an amplitude of 0.1 GPa was observed.

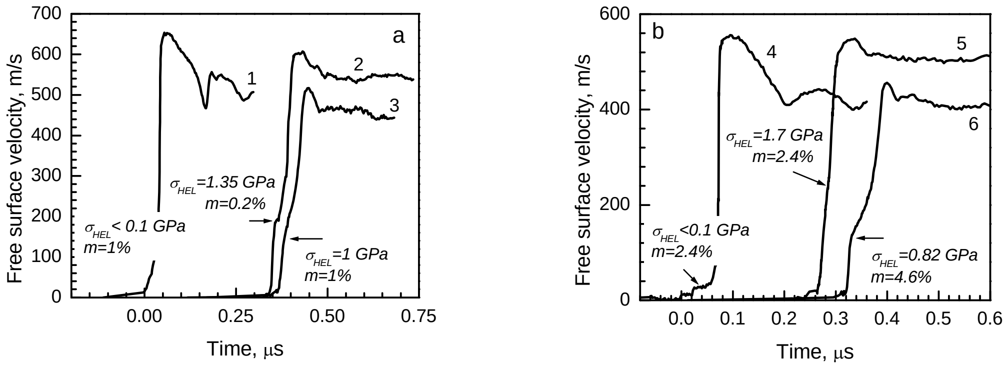

Figure 1. The free surface velocity histories from the experiments with samples of undoped aluminum Al (1, 4) and aluminum mixture Al + 5% C_{60} (2-3, 5-6) pressed under 10 kbar (a) and 7 kbar (b). The arrows indicate the Hugoniot elastic limit. The HEL values and the porosity of material are also presented in figures.

Unlike the velocity profiles for pure aluminium, the formation of the two-wave structure connected with the loss of stability of the shock wave front due to the elastic-plastic transition was registered in all experiments with mixed samples. In all experiments with the aluminum mixture Al + C_{60}, it was found that the Hugoniot elastic limit increased ten times, and increased more in less porous samples. The pressure value behind the first shock front corresponding to the Hugoniot elastic limit was calculated using the measured particle velocity history as $\sigma_{HEL} = 1/2C_L\rho_0\, u_{fsHEL}$, where C_L was the longitudinal sound velocity, ρ_0 was the initial density, and u_{fsHEL} was the amplitude of the elastic precursor. For example, the value of the Hugoniot elastic limit for the aluminium mixture sample pressed to 10 kbar was equal to 1 GPa and it increased to 1.35 GPa with the decrease of porosity from 1% to 0.2% (see figure 1). For the samples pressed under the lower pressure of 7 kbar this tendency remained. The formation of the spall impulse after the spall fracture was not observed for the mixed samples and weak random oscillations of velocity on the particle velocity histories were registered.

Figure 2 presents the results of experiments with the samples of undoped copper (profile 2) and a copper mixture Cu + 2% C_{60} (profiles 4-6) pressed under 5 - 7 kbar. It is well known that commercial polycrystalline copper has a very low HEL [4]. In our experiments on the aluminium mixture samples, the splitting of the shock wave into two was observed in the particle velocity histories. Such two wave structure may be connected with the formation of the elastic precursor at pressures higher than 1.35 GPa but below the peak compression pressure of ~3.4 GPa. The difference between the longitudinal and bulk sound velocity in copper is small, so there is a low discrepancy between the plastic and elastic waves of compression. In the experiment with the higher peak shock wave pressure of 5.6 GPa (profile 6) in the sample, we observed a sharp jump of particle velocity up to 200 – 220 m/s corresponding to a pressure of 3 GPa. In figure 3, the particle histories for the three similar samples under the same loading conditions are presented, with the region of the elastic-plastic transition shown in a magnified view. The change of the wave front with the subsequent smooth increase of pressure in the shock wave up to the maximum value was probably associated with the compaction of the material at high strain rates. This evolution of the elastic-plastic compression wave was often observed for strongly inhomogeneous materials such as sintered ceramics, various composites, and similar materials with heterogeneous structure [5,6]. The registered sharp jump of velocity in these experiments also can be interpreted as the appearance of the elastic compression wave with an amplitude of ~3 GPa on the samples' surface.

The spall strength of the copper admixed samples decreased significantly in comparison with the spall strength of undoped pressed copper and commercial polycrystalline copper.

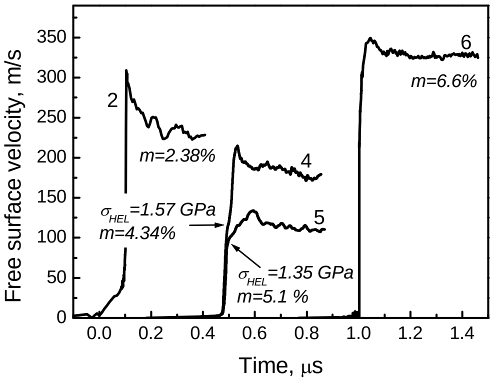

Figure 2. The particle velocity histories from experiments with the samples of undoped copper (profile 2) and the copper mixture Cu + 2% C_{60} (profiles 4-6) pressed under 5-7 kbar. The arrows indicate the Hugoniot elastic limit and the porosity of the material.

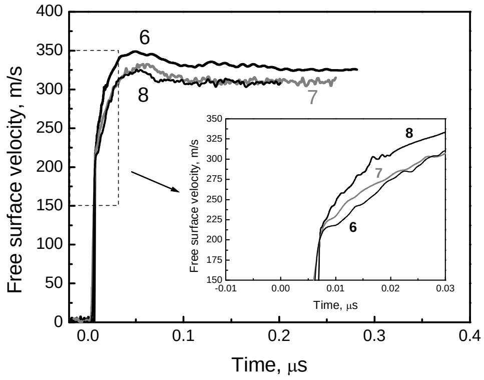

Figure 3. The particle velocity histories from experiments with the samples of copper mixture Cu + 2% C_{60} (profiles 6-8) pressed under 7 kbar.

Figure 4 presents the results of measurements of the Hugoniot elastic limit from the sample porosity for aluminum and copper samples with fullerene. For all types of mixed samples a decrease of the Hugoniot elastic limits was observed. The reason for such a strong effect of porosity on the Hugonot elastic limit of the metals tested is still unclear.

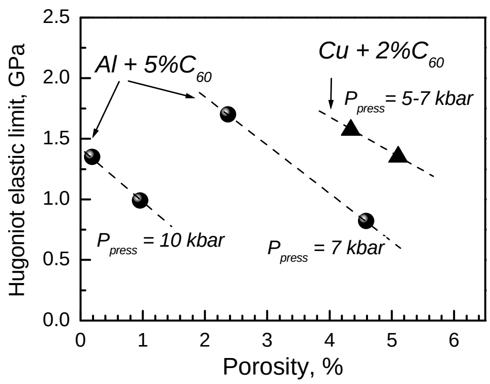

Figure 4. The dependence of porosity on the Hugoniot elastic limit for the aluminum and copper samples with fullerene.

The experimental parameters – sample thicknesses (h_{samp}) and peak pressure in shock wave (P_{max}), the measured sample properties – hardness (H_R) and porosity (m), and the results of the measurements of the Hugoniot elastic limits and the spall strengths of the aluminum and copper samples are presented in table 2. The number of the experiment in table 2 corresponds to the number of the free surface velocity histories presented in figures 1 to 3.

Table 2. The results of the measurements.

Exp #	Samples type	h_{samp} (mm)	H_R	*m* (%)	P_{max} (GPa)	σ_{HEL} (GPa)	σ_{sp} (GPa)
	Aluminum samples						
1	AD0, pressed	1.825	37.2	1.1	5.04	< 0.1	1.38
2	AD0 + 5% C_{60}, P_p=10 kbar, 280 ^{o}C	1.966	98.9	0.19	4.54	1.35	0.4
3	AD0 + 5% C_{60}, P_p=10 kbar, 280 ^{o}C	2.011	98.8	0.96	3.81	0.99	0.36
4	AD0, pressed	1.984	37.25	2.36	4.18	0.09	0.89
5	AD0 + 5% C_{60}, P_p=7 kbar, 280 °C	1.938	96.08	2.45	3.98	1.7	0.21
6	AD0 + 5% C_{60}, P_p=7 kbar, 280 °C	1.822	96.08	4.59	3.22	0.82	0.2
	Copper samples						
1	M1, polycrystalline	1.98	-	0.1	6.18	0.04	2.09
2	Cu, pressed	1.83	87.5	2.24	5.5	-	1.1
3	Cu, pressed	2.99	87.3	2.7	1.15	-	-
4	Cu + 2% C_{60} P_p=5–7 kbar, 450 °C	2.00	107.9	3.9	3.44	1.58	0.43
5	Cu + 2% C_{60} P_p=5–7 kbar, 450 °C	2.04	111.1	5.1	2.09	1.35	0.26
6	Cu + 2% C_{60} P_p=7 kbar, 400 °C	1.98	115.02	3.1	5.62	3.04	0.3
7	Cu + 2% C_{60} P_p=7 kbar, 400 °C	2.009	115.02	1.7	5.57	3.46	0.27
8	Cu + 2% C_{60} P_p=7 kbar, 400 °C	2.114	115.02	2.44	5.41	3.23	0.23

4. Conclusion

The Hugoniot elastic limit of 5% fullerene aluminum samples was higher ten times that of pure aluminum. Fullerene-copper mixtures also showed a marked increase in the Hugoniot elastic limit over pure copper. The calculated values of the Hugoniot elastic limit for the aluminum mixtures were 0.82 – 1.56 GPa, while those for the copper mixtures were 1.35 – 3.46 GPa. Both values depended upon the sample porosity. The strong growth of the dynamic elastic limit of the mixed samples was surely connected with the presence of the fullerene nanoparticles in the sample structure. The elastic limit of a material or the stress under which the material begins to deform plastically depends on the quantity of moving dislocations in the material volume [7]. The interface between the particles of the metal matrix and the harder fullerene particles is an insuperable barrier for the moving dislocations. As a result of the reduction in the quantity of moving dislocations, the elastic limit of the mixed samples sharply increases. It should be noted that structural defects of the metal samples (such as cracks) do not have a strong influence on the value of the elastic-plastic transformation, but they exert evident influence on the resistance of the mixed metals to tensile stresses. As expected, the spall strength of both aluminium and copper samples was much lower than that measured for polycrystalline metal samples without any fullerene admixture.

References

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