Study of the high-velocity impact of tungsten particles with a steel target

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Abstract. The high-velocity impact of a tungsten particle flux with the surface layer of steel (U8) samples is studied. High-speed photography which was used to record the motion of tungsten particles and detonation products shows that tungsten particles move with an average velocity of 2.4 km/s. Microstructure studies have revealed that upon the impact of tungsten particles with the surface of the target, the temperature in the active zone exceeds the temperature of the peritectoid reaction in the Fe-W system, and the polymorphic transformation of iron takes place with the formation of austenite and the dissolution of tungsten carbide in austenite under these temperature conditions.

1. Introduction

Dynamic methods associated with the use of explosion energy occupy a special place among various methods for processing materials. The energy of explosion provides high pulsed loads, resulting in the rearrangement of the structure of processed materials. The feature of explosive processing is the achievement of high pressures within short time intervals. Processes occurring during high-velocity impact represent a specific interaction region located at the boundary of mechanics, hydrodynamics, physics of shock waves and high pressures.

At present, of particular interest are the studies concerning the combination of shock wave processing and the addition of alloying additives to materials. Obtaining new metal materials by shock wave loading of a submicro- and nanostructure provides high strength characteristics and promising properties of materials. One of these methods is the processing of metals by a flux of high-velocity particles. For the case when a flux of particles up to 100 μm in size accelerated by the explosion energy to a velocity of 1000-3000 m/s interacted with a metal target, it was found that the material of these particles could penetrate into the target to a depth from hundreds to thousands of its initial diameters [1, 2]. This process is called the phenomenon of super deep penetration of particles. This phenomenon was discovered in the experiments on hardening metals using explosive loading. Structural changes in the studied material treated with a high-velocity particle flux are due to the action of shock waves created by the impact of the particle flux with a target and the effect of particles embedded in the sample [3-6]. The nature of this phenomenon has not been studied [7-10], but it can be used currently in manufacturing process, in particular, for hardening metal materials. When a high-velocity particle flux interacts with the surface of the target, the largest part of the particle flux forms a
coating from these particles, and the thickness, structure, and phase composition of the formed layer are stable. The phenomenon of super-deep penetration used as a physical tool can effectively change the physical and mechanical properties in the volume of metal products.

The purpose of this work is to experimentally study the velocity of tungsten particles accelerated by the explosion energy and directed to a steel target.

2. Materials and Methods
In the experiments we used the steel (U8) samples with a diameter of 25 mm and a height of 30 mm as a steel target and tungsten powder with a particle size of 10-16 microns. The particle size of the powder was determined using a Micro Sizer 201 laser particle analyzer.

The arrangement of the experiment is shown in Figure 1. The test sample (6) was placed in a guiding plexiglas channel (5), on top of which a ring (3) with tungsten powder (4) with a bulk density of 5 g was located. A plate-cutter (2) was mounted on the ring, so that the detonation products outside the guiding channel did not close the field of view for the four-channel electron-optical camera NANOGATE-4BP. An explosive (1), hexogen of bulk density, was placed on top of the plate. The length-diameter ratio of the explosive was 2.85, which corresponds to the condition for the initiation of a stationary detonation wave [11], and the parameters of the detonation wave and the reaction time in its front are independent of the length of the explosive. An air gap was left between the tungsten powder and the explosive to ensure a longer loading of the powder particles and form a plane shock front [12]. The experimental assembly was placed in an explosive chamber and the electron-optical camera recorded the experiment through a protective window due to the presence of damaging factors of explosion and gaseous detonation products.

![Figure 1. Arrangement of the experiment: 1 - explosive; 2 - plate-cutter; 3 - fixing ring; 4 - tungsten powder; 5 - guiding plexiglass channel; 6 - sample.](image)

During detonation, shock wave and explosion products accelerated the powder and, together with it, acted on the test sample. After processing, the samples were cut along the axis in the direction of particle flux loading. Preparation of thin sections of the samples included grinding and polishing to analyze the results. X-ray diffraction analysis of the obtained sections was performed on a LEO 1450 VP scanning electron microscope with an INCA 300 energy dispersive system (EDS).

3. Results and Discussion
The electron-optical camera can take four frames for one experiment when the test sample is subjected to the loading of the high-velocity particle flux. Photographs of high-velocity motion of tungsten particles and explosive detonation products are shown in Figure 2. The delay time for the first photograph (figure 2a) after the explosive starts to detonate is 7 μs, which is necessary for the detonation products to reach the powder layer in the fixing ring, and a ball with argon, which is mounted next to the installation for illumination, reaches the maximum glow.
The analysis of the photographs (figure 2a, 2b) showed that tungsten particles begun to move at a velocity of approximately 2.6 km/s. The determination of this velocity can be considered to be accurate due to the fact that the cloud consisting of detonation products and powder particles is more compact compared to others in photographs. But the distance traveled by the cloud is not large compared to the entire distance that the particle flux travels. Then the detonation products begin to overtake the powder particles, stretching the cloud with the detonation products and tungsten particles.

![Photographs of the motion of tungsten particles and detonation products along a guiding channel. Time interval between the neighboring photographs is 5 μs. W - tungsten particles; DP - detonation products.](image)

**Figure 2.** Photographs of the motion of tungsten particles and detonation products along a guiding channel. Time interval between the neighboring photographs is 5 μs. W - tungsten particles; DP - detonation products.

The determined velocity between the photographs in figure 2b and figure 2c is approximately 2.4 km/s, and the velocity between the photographs in figure 2c and figure 2d is 2.2 km/s. Thus, the analysis of high-speed photographing the motion of the flux of tungsten particles and detonation products in the guiding channel showed that the flux of tungsten particles moved with an average velocity of 2.4 km/s, which correlates with the previously obtained results [13].

The study of the surface of the test samples using an electron microscope revealed that after the interaction of the tungsten particle flux, a coating and a transition zone were formed on the surface (figures 3a, 3b, 3c). The thickness of the formed coating is nonuniformly distributed over the surface of the sample.

An SEM study of the surface area of a sample treated with a high-velocity flux of tungsten particles shows that the formed coating consists of tungsten particles (spectrum 3, figure 3d), iron (spectrum 4, figure 3d) and their intermetallic compound (spectrum 1, 2, figure 3d). The energy dispersion analysis data for the coating are given in Table 1. The high-velocity impact of tungsten powder particles with a steel sample releases the maximum amount of energy, which brings the system in a metastable state. The temperature in the active zone exceeds the temperature of the peritectoid reaction at 1060 °C in the Fe-W system. Under these temperature conditions, the polymorphic transformation of iron takes place with the formation of austenite and the dissolution of tungsten carbide in austenite. Upon cooling, the austenite solution is supersaturated with tungsten and stabilizes. As a result, supercooled austenite is formed in the steel structure with a grid of tungsten carbide along the grain boundaries. The same changes occur on the surface of parts during pulse implantation of tungsten carbide powder in steel (45) by the method of combined electromechanical processing [14].
Figure 3. SEM images of the coating formed from tungsten particles (a, b, c), transition zone (d).

Table 1. Energy dispersive analysis of the surface layer of the sample after impact with tungsten particles (Fig. 3d; weight %).

| Spectrum | C  | Fe   | W   |
|----------|----|------|-----|
| 1        | 4.07 | 49.05 | 46.88 |
| 2        | 4.22 | 25.34 | 70.44 |
| 3        | 3.40 | ----  | 96.60 |
| 4        | 1.79 | 98.21 | ---- |

Figure 4 demonstrates an analysis of the chemical distribution of iron and tungsten in the surface layer of the sample after processing with a high-velocity flux of tungsten particles. The analysis of this chemical distribution also shows, like the energy dispersive analysis of the coating, the joint distribution regions of iron and tungsten in the surface zone of the sample between the tungsten particles in the coating. The formation of a flat interphase intermetallic layer is observed between the formed coating and the steel sample. This suggests that these coating areas consist of an intermetallic compound Fe and W. Similar changes in the surface layer were found studying the destruction of the synthesized material in the SHS system Ni-Al-W [15].

These changes indicate the occurrence of reaction diffusion at the interphase boundary with the formation of intermetallic compounds based on the components of the composite. The authors in [15] assume that intermetallic compounds at the NiAl – W boundary grow in the direction of the NiAl compound and are determined by the diffusion mobility of tungsten atoms.

The nature of the interaction at the W and Fe boundary is completely consistent with the previously obtained experimental data for other systems, such as Cu-Ti, Cu-TiNb, Ni-Al-W. The formation and growth of a continuous intermetallic layer at the interphase boundary was shown to occur due to reaction diffusion [16].
The analysis of the photographs of the motion of a high-velocity tungsten particle flux and detonation products of hexogen in a guiding plexiglas channel showed that tungsten particles moved with an average velocity of about 2.4 km/s.

The studies of the microstructure of the near-surface zone in steel (U8) samples treated with a flux of tungsten particles showed the formation of a tungsten particle coating, which is a composite consisting of tungsten, iron and their intermetallic compound. It was revealed that upon the impact of the flux of tungsten particles with the surface of the target, the temperature in the active zone exceeds the temperature of the peritectoid reaction in the Fe-W system, and the polymorphic transformation of iron takes place with the formation of austenite and the dissolution of tungsten carbide in austenite under these temperature conditions.

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