Features of interaction of powder high-velocity particles with the surface layer of the target

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Abstract. The interaction of a stream of high-velocity particles with the surface layer of a target was investigated. The impact of discrete particles with the sample surface was shown to lead to the formation of a coating consisting of these particles and to the changes in the physical and mechanical properties of the surface layer of the target. The obtained coatings are a composite material consisting of sintered (not melted) powder particles. The impact of high-velocity particles was shown to lead to the hardening of the surface layer of samples exposed to the stream of powder particles of tungsten, nickel and titanium nitride. The maximum increase in the microhardness of targets was observed at a depth of 2 and 4 mm from the surface treated with a stream of particles.

1. Introduction

Dynamic methods that use explosion energy occupy a special place among a large number of different methods for the processing of materials. One of these methods is shock-wave interaction of the stream of discrete particles with targets, when the material of these particles can penetrate into a target, at a depth exceeding the size of initial particles by hundred times [1–5]. This effect was discovered by Soviet scientists S. M. Usherenko in the experiments conducted for the hardening of metals subjected to explosives in the 70s of the last century. This effect is reached when a target is exposed to a stream of high-velocity particles by two main schemes: location of the powder particles in the cumulative cavity of the explosive [6] and frontal throwing of particles [7].

Shock-wave loading and impact of high-velocity particles provide improved physical and mechanical properties of both the surface and the entire volume of the materials treated. Researchers focus on the near-surface zone, where the main processes take place in the study of materials treated with a stream of high-velocity particles [8–11]. When a stream of high-velocity particles interacts with a target, most of the particles remain in the near-surface zone and form a coating. At the same time, the formed layer is stable in thickness, structure and phase composition. The formation of a special structure due to the high-velocity interaction of powder particles with a steel target allows materials to be obtained with new properties.

The purpose of this work is to study the effect of various powder particles accelerated by the energy of an explosion on the surface layer of a steel target.

2. Materials and Methods

Targets made of structural steel (grade St.3) were subjected to shock-wave treatment with a stream of discrete high-velocity particles of the powders such as tungsten with a particle size of 10–16 μm, nickel with a particle size of 6–16 μm and titanium nitride with a particle size of 45–60 μm accelerated
by an explosive to study the structure and properties of the near-surface layer of these targets. To
determine the particle size of the powders, a Micro Sizer 201 laser particle analyzer was used.

The scheme of the experiment was as follows: a cylindrical sample was placed in a guide channel,
on top of which was a ring with a powder material with a bulk density of 3 g. An explosive with a
detonator was placed on the ring [12]. There was a gap between the powder particles and the
explosive. The gap provided a longer powder loading which is necessary to create a rectangular shock
pulse. During detonation, the test sample was subjected to shock wave and explosion products, as well
as to the treatment with a powder accelerated by them. Hexogen was used as an explosive. In all
experiments, mass, type of explosives and the scheme of treatment were constant.

Vickers hardness of the near-surface zone of the samples was measured after treatment with a
stream of high-velocity particles and in the initial state using a PMT-3 hardness meter under a load of
100 g. The SEM study of the samples was conducted using a Zeiss Ultra plus scanning electron
microscope and a metallographic inverted microscope METAM LV-34 with a camera MC-5.3.

3. Results and Discussion
A shock-wave treatment of a steel sample with a stream of particles leads to the formation of a
transition zone and a coating on the sample surface. Figure 1 shows that the thickness of the coatings
formed by powder particles is distributed nonuniformly over the surface of the target and is not
continuous, and there are cavities as well. This confirms that the particles of the powders are in the
unmelted state while interacting with the surface of the samples, and the coating consists of sintered
particles.

![Microstructure of the samples exposed to powder high-velocity particles](image)

Figure 1. Microstructure of the samples exposed to powder high-velocity particles of (a, b) tungsten, (c) nickel, and (d) titanium nitride.

A similar result was obtained in the estimated calculations. Calculations of the thermal effect of the
detonation products on the powder particles flying with them and the temperatures of particles reached
during a high-velocity interaction with a target showed that the time during which the powder particles
interact with the detonation products is not sufficient to reach the melting temperature [13].

The SEM study of the near-surface zone of the etched sample (figure 1a) with the use of the
electron microscope shows that a clear boundary is observed between the steel target and the coating.
created from powder particles. This means that after the shock-wave interaction of powder particles with the steel target, a 2–3 μm-thick transition zone is formed, which can be seen after etching (figure 1a) or at higher magnification (figure 1b).

The energy-dispersive analysis of the samples treated with a stream of nickel particles showed structural changes detected in the near-surface layer of the target (figure 1c).

The metallographic analysis of the microstructure of the near-surface zone in the samples treated with a stream of powder particles have shown that the shock-wave treatment of samples with particles leads to grinding, flattening and stretching of ferrite and perlite grains in the near-surface layer of the samples (figure 1d). Such changes in the structure of steel are caused by both shock wave and the thrown particles of tungsten, nickel and titanium nitride powders.

The study of the microhardness distribution in the samples showed that the microhardness of the target increased after the treatment with the stream of particles. The maximum increase in the microhardness of samples is observed in the near-surface layer (figure 2) and then it decreases beginning from the surface of the treated samples. Approximately at a depth of 15–20 mm, the microhardness is about 170 units of hardness, as for the initial material, (grade St.3), since the effect of shock wave and powder particles on the structure of the steel target decreases with the distance from the contact surface of the sample.

Figure 2 shows the distribution of microhardness across the width of the samples exposed to the particles of (a) tungsten powder, (b) nickel, and (c) titanium nitride.

Figure 2. Distribution of microhardness across the width of the samples exposed to the particles of (a) tungsten powder, (b) nickel, and (c) titanium nitride.
The microhardness measurements in the near-surface layer after the shock-wave treatment with the stream of the particles are given in Table 1 that shows that the maximum increase in the microhardness by 51% and 54% is observed after the treatment with nickel particles at a depth of 2 and 4 mm.

|       | Microhardness, kgf/mm² |       |       |
|-------|------------------------|-------|-------|
| W     | 235–240 ↑42%           | 230–235 ↑39% | 210–215 ↑27%         |
| Ni    | 250–255 ↑51%           | 255–260 ↑54% | 200–205 ↑21%          |
| TiN   | 210–215 ↑27%           | 225–230 ↑36% | 205–210 ↑24%          |
| Steel | 165–170                |       |       |

The interaction of high-velocity particles of tungsten, nickel and titanium nitride with the surface of the steel target forms a coating with a thickness from 10 μm to 30 μm on the surface of the treated samples. The obtained coatings according to the results of experimental studies, calculations of the effect of detonation products on flying particles and the temperatures reached during interaction with the target are a composite material consisting of sintered (not melted) powder particles.

Studying the microhardness of the surface layer of steel targets treated with a stream of powder particles accelerated by the energy of explosion have shown that there is an increase in microhardness by at least 21% after the treatment with the powder particles under study, and the maximum increase in microhardness is observed at a depth of 4 mm from the surface treated with nickel particles.

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