Structural changes after high-speed impact of tungsten powder with a steel target

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Abstract. Shock-wave high-velocity impact of tungsten powder with a steel target was studied in the work. It is determined that shock wave treatment of the samples leads to a refinement, flattening and stretching of ferrite and perlite grains in the surface layer. The structural transition from plate perlite in the near-surface layer of the target to coarse-plate perlite in the bulk of the target, the microstructure of which does not differ from the microstructure of the initial sample, was detected in the structure of U8 steel after a particle flux. It is found that cellular supercooled austenite with tungsten carbide mesh along grain boundaries is formed in the structure of steel. The microhardness of the target in depth after exposure to tungsten particles is analyzed. It was shown that the microhardness distribution along the width of the sample is wave-like, and the microhardness decreases monotonically along the depth of the sample. The microhardness maximizes by 24\% at a distance of 4 mm from the surface compared to the original microhardness.

1. Introduction

Study of structural transformations in metal materials exposed to a flux of high-energy microparticles is an important task of physical materials science, because the impact of the particles dispersed by the explosion energy, combined with shock-wave loading of detonation products lead to the improvement of physico-mechanical properties as the surface layer and throughout the volume of the obstacles. When a flux of different particles accelerated by explosion energy up to a velocity of 1–3 km/s interacts with a target surface, their material can penetrate into the target to a depth exceeding the size of initial particles by hundreds of times and affects the material structure of the sample. This effect was found studying the hardening of metals under shock-wave loading and this process is called the phenomenon of super deep penetration of particles [1, 2]. During the interaction of detonation products with powder particles in an explosive wave, these particles are entrained due to inelastic impact of molecules of detonation products with particles. The interaction of the flux of particles with the sample stops the most of them in the near-surface zone and results in the formation of a particle coating on its surface [3–7]. Shock-wave loading and impact of high-velocity particles provide improved physical and mechanical properties of the surface and the whole volume of the processed 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. Despite the fact that the nature of this effect has not yet been established [8–11], the method of the study closely simulates the impact of space debris with aircrafts in outer space.
The purpose of this work is to study the structural transformations in the steel target after high-velocity impact with tungsten powder.

2. Materials and Methods
Tool steel samples (U8 grade) with a diameter of 25 mm and a height of 30 mm were used as a steel target. The shape of the samples was chosen for the convenience of conducting experiments. Tungsten powder with a particle size of 10–16 μm was used. The particle size of the powder was determined on a Micro Sizer 201 laser particle analyzer.

The experimental arrangement is shown in Figure 1. The test sample (6) was placed into the directing tube (5), on top of which was a ring (3) with tungsten powder (4) with a bulk density of 5 g. A cut-plate (2) was installed on the ring in order for the detonation products to fly into the directing tube (5). Hexogen with a bulk density used as an explosive (1) was placed on the plate. An air gap was left between the tungsten powder and the explosive to provide a longer powder loading resulting in the formation of a flat shock-wave front [12]. The length-to-diameter ratio of the explosive was 2.5, which meets the condition for the generation of a stationary detonation wave [13] and the stable formation of a flux of particles. After detonation, the test sample was exposed to the flux of powder particles accelerated by shock wave and explosion products.

![Figure 1. Experimental arrangement: (1) explosive charge; (2) cut-plate; (3) support ring; (4) tungsten powder; (5) directing tube; (6) obstacle (steel target).](image)

Steel targets after high-speed processing were cut along the axis along the direction of loading by a stream of tungsten particles. Sample preparation included grinding and polishing operations for metallographic studies. The samples were studied by SEM using a Zeiss Ultra plus ultra-high-resolution scanning electron microscope and an Axiosvert 200 MAT metallographic inverted microscope. The Vickers microhardness of the samples after interaction with a high-velocity flux of particles and in the initial state was measured using a PMT-3 hardness meter under a load of 100 g.

3. Results and Discussion
A metallographic analysis of the microstructure of samples treated with the high-velocity flux of tungsten particles showed that the shock-wave particle treatment of samples results in the grinding, flattening and extension of ferrite and perlite grains in the near-surface layer.

Figure 2a shows the microstructure of the initial steel sample (U8 grade) with the presence of lamellar perlite. A large number of the traces of particles are observed (black inclusions) at a distance of 2 mm from the sample surface treated with tungsten powder (figure 2b). Such traces are not observed for the sample treated only with a shock wave (experimental conditions are the same). This suggests that these traces are created by tungsten particles. Analysis of the microstructure of the near-surface zone shows the presence of a small amount of macrolamellar perlite. This is explained by the deformation of cementite plates under shock wave loading with penetrating particles with a pressure of
more than 13 GPa and by the formation of defects remaining in the lattice after the passage of shock wave.

To obtain an estimate of the collision pressure of the flow of tungsten particles as a porous body with a steel barrier, the technique of matched impedances was used. In the calculation, the Hugoniot adiabat for tungsten particles was constructed according to the data of [14], where experimental data on the determination of wave velocities in porous samples are presented. The calculations were carried out using the laws of conservation of thermodynamic parameters of shock compression. The calculations showed that the pressure in the incoming shock wave in steel is 34 GPa (the particle flux porosity $m = 3.9$). With porosity $m = 4.5$ pressure is 25 GPa. At a porosity of $m = 8$ (this value most closely matches the porosity of the tungsten particle flux during the experiment), it equals $10-13$ GPa. The latter value is consistent with the results of [15], where the authors of the work obtained a pressure of 12 GPa.

![Figure 2](image_url)

**Figure 2.** Microstructure of the steel sample (U8 grade) before (a) and after impact with tungsten particles at a distance from the surface: (b) 2 mm; (c) 6 mm; (d) 10 mm.

Analysis of the microstructure of samples treated with tungsten particles at a distance of 6 mm and 10 mm (figure 2c, figure 2d) shows that the number of the traces of particles decreases significantly compared to these samples at a distance of 2 mm. This is related to the fact that a large number of particles stop on the surface, forming a tungsten coating. Also, the shape and size of the traces of these samples change; they are oval and smaller, compared to the same samples at a distance of 2 mm. Analysis of the microstructure revealed that the content of the lamellar perlite increases in comparison with a distance of 2 mm. This is explained by the fact that at a distance of 6 mm and 10 mm from the surface, the effect of shock wave and powder particles on the structure of the sample material decreases, resulting in less heating compared to the surface layer.

Given the fact that the most tungsten particles stop on the surface during high-velocity impact with the sample, forming a coating, the near-surface area of the sample was studied. The SEM study of the
interface between the sample and the coating after impact with a flux of tungsten particles revealed a transition zone (figure 3a) consisting of the particles of tungsten (white zone - spectrum 1), iron (gray zone - spectrum 4) and their intermetallic compound (light gray zone - spectrum 2, 3). The data of energy dispersive analysis are presented in Table 1. Analysis showed a high carbon content that was explained by the fact that the thin sections of the samples were polished using diamond paste.

![Figure 3. Interface between the sample and the tungsten coating: (a) transition zone of the interface; (b) austenite cellular structure with tungsten carbide mesh.](image)

| Spectrum | C   | Fe  | W    |
|----------|-----|-----|------|
| 1        | 36.53 | 1.07 | 62.41 |
| 2        | 39.26 | 36.47 | 24.27 |
| 3        | 34.82 | 53.29 | 11.89 |
| 4        | 32.95 | 67.05 | ----- |

Higher magnification of the transition zone (figure 3b) shows the presence of the cellular austenite structure with a tungsten carbide mesh along the grain boundaries of the intermetallic compound. That is, during impact of tungsten particles with steel, the temperature exceeds the temperature of the peritectoid reaction in the Fe-W system, resulting in the formation of high-carbon austenite, which is stabilized by dissolved tungsten during cooling, and a mesh cellular structure is formed [4].

![Figure 4. Distribution of microhardness over the width of the sample after impact with tungsten particles at different distances from the surface.](image)
The study of microhardness showed (figure 4) that its distribution over the width of the sample was wave-shaped, and it monotonously decreased to the depth of the sample. The microhardness of the sample after exposure to tungsten particles at a depth of 20 mm is approximately equal to the initial microhardness of U8 steel, which was annealed to a temperature of 500 °C and has a microhardness of 180 HV. It is seen that at a depth of 2 mm microhardness is less than at a depth of 4 mm. This is related to the fact that caverns are formed on the sample surface after impact of tungsten particles with the target. The average microhardness values are 215 HV at a depth of 2 mm, which is more than the microhardness values for the initial sample. The maximum average value of microhardness is 224 HV at a distance of 4 mm from the surface and varies in the range from 214 to 230 HV.

4. Conclusion

Studies of the microstructure of U8 steel samples treated with a high-speed stream of tungsten particles showed that the impact of particles in combination with shock-wave loading of detonation products is accompanied by a refinement of the perlite structure with a transition from lamellar perlite in the surface layer of the barrier to coarse plate perlite in the volume of the barrier, which does not differ from microstructures of the initial sample of steel U8.

It was revealed that when a flux of tungsten particles interacts with a target surface, the temperature in the reaction zone exceeds the temperature of the peritectoid reaction in the Fe-W system. As a result, cellular supercooled austenite with a tungsten carbide mesh along the grain boundaries is formed in the steel structure, which is identical to the structure of cast high-speed steel with complex carbide eutectic resembling ledeburite and located along the austenite grain boundaries.

A study of the microhardness of the target after treatment with a tungsten particle stream showed that the microhardness distribution along the width of the samples is wave-like, and the microhardness decreases monotonically along the depth of the samples. The study of microhardness of the target after treatment with a flux of tungsten particles showed the increase in microhardness compared to the initial microhardness of steel (U8 grade). The maximum increase in microhardness by 24% occurs at a distance of 4 mm from the processing surface in comparison with the initial microhardness.

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