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STRUCTURE, PHASE TRANSFORMATIONS, AND DIFFUSION

Effect of Extreme Impacts on the Structure and Properties of Alloys

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Abstract—This paper presents the results of research on the effect of extreme impacts on metals and alloys. This research was performed over the last 25 years in the physical metallurgy laboratory of the Mikheev Institute of Metal Physics, Ural Branch, Russian Academy of Sciences. For the purpose of this study, the following extreme impacts are considered: strong magnetic fields, laser heating, shock-wave loading, severe plastic deformation by dynamic channel-angular pressing and shear under pressure, and frictional surface treatment by dry friction.

Keywords: strong magnetic fields, laser heating, shock waves, dynamical channel-angular pressing, friction treatment

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Scientists have devoted a significant amount of time and attention to the study of extreme impacts on the structure and properties of metals and alloys. Twenty-five years ago, under the supervision of Sadovskii (August 6, 1908—February 17, 1991), scientists at the Mikheev Institute of Metal Physics, Russian Academy of Sciences (IMP RAS) began to study the effect of magnetic fields on martensitic transformation. To detect these effects, it was necessary to use dc or pulsed magnetic fields of maximum possible strengths. We have discovered the effect of a magnetic field on martensitic transformations in iron alloys, in which the nonferromagnetic phase (austenite) transformed into ferromagnetic phases and structures (martensite, bainite, pearlite). A detailed study was made of the microstructure of martensite formed in steels of different chemical composition under a high-strength pulsed magnetic field. It was established that a magnetic field leads to changes in the morphology of martensite, and that in steels with isothermal transformation kinetics, athermal martensite can be produced.

This was the first time that a pulsed magnetic field made it possible to clearly separate the formation of lenticular crystals of martensite into two successive stages: the formation of a twinned middle part of the crystal (midrib) and a further growth of the crystal width, at which the peripheral dislocational part of the crystal is formed. During the crystal growth period, the deformation mechanism with the invariant lattice changes from twinning in the midrib to slip. The effect of a strong dc magnetic field on the alloy with isothermal kinetics of martensitic transformation demonstrated that the C-shaped curve, which describes the kinetics of the transformation, shifts to the left (in time) and upward (in temperature); i.e., the transformation is accelerated and leads to an increase in the amount of martensite. We also found that the application of a dc magnetic field reduces the incubation period of the pearlitic transformation and leads to its acceleration. This effect produced by magnetic fields was expected, but quantitative data on this were obtained for the first time. The results of these studies have been illustrated in the monographs [1, 2].

Sadovskii also initiated the study of changes in the structure and properties of alloys at extremely high heating rates that occurred when laser irradiation was applied [3]. The phenomenon of structural heredity was clearly manifested in the case of laser heating. At a very high rate of heating by the laser beam, the formation of austenite in the quenched steel occurred via a mechanism close to martensitic and was accompanied by the reproduction of the original structure of the austenite. The two stages of the transformation upon heating (the formation of a restored austenite structure upon the $\alpha \rightarrow \gamma$ transformation and the subsequent recrystallization) were clearly separated. We observed cases where the steel with a restored austenite grain underwent melting, and there was no time for recrystallization to occur, therefore the second stage was absent, and Chernov's "b" point disappeared. Upon laser heating of steel with a pearlite structure, a diffusionless (martensitic) mechanism of austenite formation was detected. There was not enough time at a high heating rate for cementite plates to dissolved, and under such nonequilibrium conditions, the ferrite of the pearlite transformed into austenite, and the front of the $\alpha \rightarrow \gamma$ transformation propagated between the cementite plates. The results of these studies were illustrated in [4].

The results of studies investigating the effect of strong shock waves on the materials are being examined with increased interest. These investigations began in the laboratory of physical metallurgy at the IMP. They began after Deribas, a well-known scientist [5] from the Lavrent'ev Institute of Hydrodynamics, Siberian Branch, Russian Academy of Sciences, appealed personally to Sadovskii. An original study was performed, in which the formation of extremely dispersed (nanosized) austenite crystals in an iron–nickel alloy were detected under the action of shock waves at pressures of 20–39 GPa [6]. Subsequently, a number of studies on the strengthening of austenitic steels under the action of normal and oblique shock waves were performed. These studies showed that to obtain a strengthening effect, it is sufficient to apply shock waves with a relatively small pressure amplitude, 10–15 GPa [7].

This area of study has been actively developed since 1992 in cooperation with scientists from the Russian Federal Nuclear Center, Research Institute of Technical Physics (RFNC-RITP), under the overall supervision of Litvinov, the chief designer of nuclear charges. The specificity of these works is in the loading of metallic materials with converging shock waves, which allows us to investigate the behavior of materials under extreme conditions. Upon the implosive loading of solid metal balls, the shock waves propagate from the surface to the center, interact with each other, and are focused in the center of the sphere. From this, we can observe complex phenomena of the interaction of shock waves, energy cumulation (or its absence), phase transformations, etc. These processes occur in a few millionths of a second, and it is a difficult task to observe them directly. The application of physical metallurgy methods to study residual changes in the microstructure of samples preserved after implosive loading was extremely productive. A number of studies have investigated relationships between the loading parameters (ultrahigh pressures, up to 300 GPa; high-speed deformations, 10^7 s^{-1}; temperatures up to 2000°C) and structural changes, most of which are caused by localized-deformation effects, polymorphic transformations, melting, and subsequent crystallization.

Metallographic studies of loaded samples reveal the pattern of propagation, collision, and focusing of shock waves using etching figures, which we called Altshuler's figures. The geometry of these figures and the study of the structure in different regions of the sample allowed us to determine the attenuation of shock waves and the type of interaction of neighboring waves (Mach-type or regular), to find the region of focusing, to determine different times of initiation of charges, and to find the magnitudes of pressure and residual temperature [8, 9]. For example, Fig. 1 shows

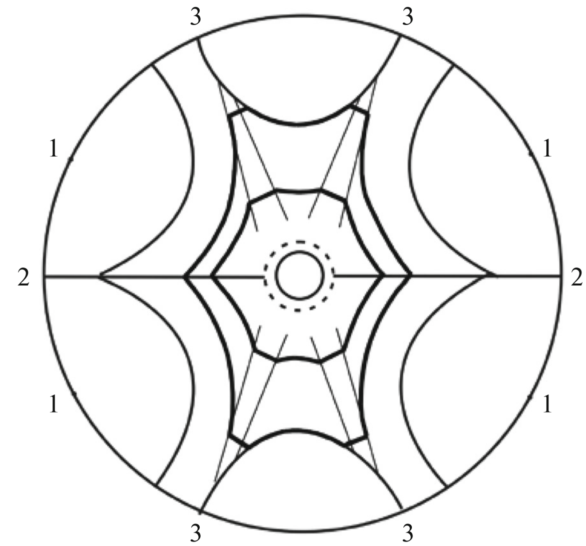

Fig. 1. Scheme of focusing of shock waves in the diametrical section of a ball: (1) projections of the points of initiation; (2) regular interactions (collision of two waves at the edges of the dodecahedron); and (3) Mach configurations (collision of three waves at the vertices of the dodecahedron). The circle in the center is the region of focusing.

the scheme of propagation, interaction, and focusing of shock waves under a quasi-spherical (12 points of initiation) implosive loading of a ball with a diameter of 40 mm made of 12Kh18N10T steel [10]. The scheme is constructed based on the results of a study of the sample preserved integer and reproduces the picture of focusing, which leads to the cumulation effect. Studies which investigate deformation and thermal processes occurring during the collapse of thick-walled cylindrical steel and copper shells under the action of sliding shock waves are currently under way [11]. It is important to emphasize that the shock-wave loading and high-strain-rate deformation cause phase and structural transformations in metallic materials that differ from those that occur when using quasi-static methods of action. This creates new opportunities for controlling the structure and properties of materials.

A lot of attention has been paid in recent decades to studies of large and very large plastic deformations [12], which produce nanocrystalline and submicrocrystalline structures in metals and alloys. The creation of such structures leads to an increase in the mechanical and some service properties of materials [13]. Rybin was the first to substantiate and prove that under the effect of large plastic deformations, grain boundaries of deformation origin arise, which are a "structural response to the development of rotational modes of plasticity" [12]. Severe plastic deformation (SPD), the conditional boundary of which corresponds to the value of the true strain greater than unity, leads to the formation of a cellular dislocation structure. The size of the cells varies from hundreds to tens of nanometers and decreases with increasing true deformation; the cells have smeared, 'fluffy' boundaries [13]. SPD is usually carried out under high pressure, which prevents destruction. The basic methods of severe deformation are equal-channel angular pressing (ECAP) and shear under high pressure in Bridgman anvils (high-pressure torsion, HPT). Upon the HPT, the deformation cells obtained are smaller than in the case of ECAP, but the size of the samples that can be treated by HPT is very small, which limits the possibilities of subsequent application. Upon the SPD by the HPT method, phase transformations occur that are not observed upon deformation by other methods. Therefore in the titanium nickelide (TiNi), the B19' martensite is transformed upon SPD into an amorphous phase [14]; in titanium, a high-pressure ω phase is formed [15]. The process of amorphization in TiNi begins after one rotation of the anvil; after 3.5 rotations, it is almost completed. The formation of an amorphous state in TiNi is an important step necessary for obtaining a homogeneous nanocrystalline structure during subsequent crystallization [14]. Such a structure provides an increase in the mechanical properties and memory properties, in particular, in the reactive stress.

The SPD of metals by the ECAP method proposed in [16, 17] has been widely accepted in the scientific community. Numerous studies of metallic materials were aimed at determining the best ECAP regimes for obtaining nanocrystalline structures and increasing mechanical properties [13]. In the RFNC-RITP, a method of dynamic channel-angular pressing (DCAP) was proposed, which is a high-strain-rate version of the ECAP. In the DCAP method, explosion energy is used instead of expensive pressing equipment. Structure formation in the case of DCAP is carried out due to a combined effect of high-speed shear strain, shock-wave compression deformation, and temperature increase. We have established that in order to obtain comparable results, fewer passes are required upon DCAP than upon ECAP. For the determination of the true uniform shear deformation in the course of dynamic channel-angular pressing, a geometrical method was proposed. This method is based on a metallographic study of the spatial orientation of structural components. We studied the structure and the physicomechanical properties of titanium, copper, and chromium–zirconium bronzes of different chemical composition deformed by the DCAP method under different regimes. It was shown that for the DCAP of titanium an increase in the deformation temperature to ~500°C is necessary [18]. In copper, periodically repeated processes of fragmentation, dynamic polygonization, and dynamic recrystallization occur upon DCAP. The structure of the chromium–zirconium bronzes upon DCAP is formed due to fragmentation, dynamic polygonization, and deformation-induced aging with the precipitation of nanoscale particles of a copper–zirconium phase at dislocations. The precipitation of nanoscale particles during subsequent annealing (aging) delays recrystallization processes and substantially increases the thermal stability of the obtained state. We demonstrated that the use of four cycles of DCAP leads to a dispersion of the microstructure of the investigated bronzes to a nanoscale level and increases the strength characteristics after aging by three times, maintaining a satisfactory level of plasticity [19].

A unique method of severe plastic deformation has been developed in the laboratory and used successfully to obtain a nanocrystalline state in surface layers (up to 10-μm thickness) of metals and alloys due to friction treatment in the dry-friction regime. We have created original devices for tribological testing under different conditions of frictional loading (load changes, sliding speed, temperature, medium). It has been established that frictional treatment by certain regimes leads to a significant hardening of the surface and also substantially accelerates processes that occur during subsequent thermochemical treatment (oxidation, nitriding) [20, 21]. The effect of martensitic $\gamma \rightarrow \alpha$ and $\gamma \rightarrow \varepsilon$ transformations on the main tribological properties of austenitic steels has been demonstrated [22]. We also found a strong positive effect of deformation dynamic aging on the resistance of martensitic and austenitic steels to various types of wear (adhesive, abrasive, fatigue). Wear-resistant austenitic steels and methods for hardening the surface of titanium and titanium nickelide have been developed as the result of our studies and these are protected by 22 Russian patents and author's certificates.

Even upon a brief consideration of the work done in the laboratory, it can be concluded that the studies of the influence of extreme effects on the structure and properties of metals and alloys are continuing to develop and expand.

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