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STRUCTURE FORMATION PROCESSES IN THE PRODUCTION OF A LAMINATED STEEL-COPPER-BRASS COMPOSITE BY EXPLOSION WELDING

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ABSTRACT
A layered composite material consisting of 20-grade steel, M1 copper, and L80 brass produced by explosive welding was studied. Under explosive welding conditions, complex mechanochemical transformations occur within the contact region of the multilayer composite material, resulting in the formation of phases that are absent in the equilibrium state of the original constituents. In particular, the emergence of the Cu_5Zn_8 intermetallic phase and metastable γ-iron has been identified. The development of this microstructure is associated with high-rate interdiffusion processes, including the penetration of copper into iron and the migration of zinc from the brass layer into copper. The evolution of these phenomena is governed by the wave-like dynamics of material interaction in the welded interface zone. The microhardness of the layers of the resulting composite material was also studied.

INTRODUCTION

The study of structural transformations of nonequilibrium excited states in metals and alloys is a key problem in condensed matter physics, the scope of which is constantly evolving as experimental techniques and theoretical concepts develop.

The processes of structural self-organization during phase transformations in metals were first described in the works of D.K. Chernov. The formation of structural states arising in deformation localization zones in metallic alloys has been extensively studied.

According to Prigogine, new nonequilibrium structures are created in a system of excited atoms with decreasing entropy. An arbitrary nonequilibrium system tends toward a local equilibrium state at extreme speed (with maximum entropy production). Experimental data show that technological processes generally occur under conditions significantly removed from equilibrium. Consequently, minor changes in the system's parameters can lead to significant changes in its physical and mechanical properties.

One area of practical application that utilizes fast processes in metal alloys is the creation of materials with high strength, ductility, impact toughness, wear resistance, and other properties. Understanding the structural formation patterns of such materials allows us to predict their new properties.

Under conditions of structural instability, as well as in internal stress fields created by plastic deformation, nanostructured formations can arise, the properties of which determine the macroscopic properties of the material. Therefore, new experimental studies are needed to identify and explain the general patterns and nature of structural and phase transformations in such materials for the subsequent use of their unique properties in engineering and industry.

Investigations into the properties of composite materials and the physicochemical phenomena associated with explosive welding contribute to the development of materials exhibiting unique performance characteristics, thereby creating new opportunities for addressing contemporary engineering challenges. Metal matrix composites (MMCs) composed of dissimilar metals with limited mutual solubility are of particular interest due to their ability to combine the advantageous properties of individual constituents within a single material system. As a result, such composites demonstrate significant potential for a wide range of applications. For instance, copper-based composites reinforced with refractory metals are characterized by high mechanical strength and excellent thermal stability. Previous studies have shown that increasing the volume fraction of the refractory phase leads to enhanced hardness in copper–molybdenum composites. These advanced materials are therefore considered promising candidates for applications such as the manufacture of resistance welding electrodes and other high-performance electrical components.

The cluster modeling approach is based on representing each structural state as a combination of elementary crystalline clusters. Cluster aggregates are formed by the assembly of these elementary clusters, which may consist of simple atomic configurations, such as octahedra and tetrahedra, or more complex structural units. The fundamental concept of the method is that polymorphic transformations are described not in terms of the relative displacement of atomic planes, but rather as a reconstruction of three-dimensional coordination polyhedra that constitute the crystal structures of the phases involved in the phase transformation.

Structures composed entirely of tetrahedra exhibit an exceptionally high packing efficiency, reaching approximately 89%, which is significantly greater than that of the closest-packed crystalline arrangements, namely face-centered cubic (FCC) and hexagonal close-packed (HCP) lattices, whose packing density is about 74%. The presence of such structural units in liquid or amorphous metals may account for their relatively high atomic packing density, typically ranging from 71% to 73% in amorphous alloys, whereas the calculated density of random close packing does not exceed 64–66%. Since the packing density of amorphous alloys containing icosahedral phases is somewhat lower than that of densely packed FCC, HCP, and body-centered cubic (BCC) structures, these materials can be regarded as having a comparatively more open atomic arrangement. A systematic analysis of icosahedral configurations in metallic systems was first presented by Frank and Kasper, who demonstrated the feasibility of their formation and identified four principal cluster types, including the simple icosahedron. To date, numerous structures classified as tetrahedrally close-packed phases have been reported, particularly in structurally unstable states associated with plastic deformation. Furthermore, several studies have shown that icosahedral phases can be produced through mechanochemical processing. Our investigations have likewise revealed the formation of tetrahedrally close-packed structures during plastic deformation in nickel–titanium alloys, Hadfield steel, and cast iron.

Solid-state phase transformations induced by plastic deformation have become a subject of considerable research interest in recent years. Under mechanical loading, mechanochemical reaction products may form at the interfaces between dissimilar metals. The exceptionally high rates of physicochemical transformations observed in such systems are associated with the propagation of plastic deformation waves, which act as carriers of both energy and mass. Under conventional static conditions, the formation of new phases typically requires relatively long periods of time, ranging from seconds and minutes to hours or even longer. In contrast, when transformations occur within plastic deformation waves, they can be completed within extremely short time intervals on the order of 10^{-5}–10^{-7} s. The resulting phase particles may reach sizes of several tenths of a millimeter or larger. Moreover, the newly formed phases are generally characterized by a nonequilibrium nature.

Nonlinear mass-transfer waves propagate through a relay-like mechanism in which atoms are successively transferred from regular lattice sites to bifurcation sites. Each bifurcation site, in turn, displaces an atom from the neighboring lattice position into the nearest bifurcation interstitial state, thereby enabling the continued propagation of mass transport through the crystal structure. This mechanism differs fundamentally from conventional diffusion. In diffusion processes, the same atoms migrate along the entire transport path through regular lattice sites, without the involvement of intermediate bifurcation states. Consequently, nonlinear wave-driven mass transfer represents a distinct transport mode characterized by the participation of transient bifurcation configurations that are absent in classical diffusion mechanisms. One elementary act in a nonlinear wave consists of an atom transitioning from a main site to an interstitial bifurcation state and pushing the next atom from its main site to the nearest interstitial bifurcation state. This relay-type mass transport mechanism is characterized by an anomalously high propagation rate compared with conventional diffusion processes. Owing to the successive transfer of atomic displacements rather than the long-range migration of individual atoms, mass transport can occur over extremely short timescales and with significantly greater efficiency than diffusion-driven atomic motion.

In a crystal containing a substitutional solid solution, impurity atoms subjected to a nonuniform mechanical stress field experience a driving force proportional to the local stress gradient. As a result, stress-induced atomic migration may occur, contributing to enhanced mass transfer and promoting structural and phase transformations within the material:

$$f_v = \Omega_0 \nabla P \quad f_i = -\Omega_0 \nabla P \tag{1}$$

Ω_0 - volume of a point defect;

∇P - local pressure change.

The flux density of the substance J creates a concentration gradient and leads to the stratification of the alloy, as occurs with ascending diffusion:

$$J = D \nabla C \tag{2}$$

D- mass transfer coefficient, similar to the diffusion coefficient.

Estimates based on the proposed model indicate that this mode of atomic displacement proceeds at an average velocity of approximately 4.5×103 m/s. The model provides a framework for explaining the phenomena of anomalously rapid mass transport and ion segregation observed in metallic alloys subjected to plastic deformation. Furthermore, it offers insight into the underlying mechanisms responsible for the accelerated redistribution of chemical species under nonequilibrium deformation conditions.

Layered composite materials are currently attracting significant attention because they offer the possibility of achieving unique combinations of mechanical and physical properties. Composites incorporating copper- and steel-based layers are particularly valuable for the manufacture of components used in electrothermal systems, heat-exchange equipment, and other engineering applications. However, producing composites from materials with limited weldability remains a considerable technological challenge (Vainerman & Pichuzhkin, 2002). These difficulties can be overcome through the application of high-energy material-processing techniques, such as explosive welding (Kveglis et al., 2016). Nevertheless, the physicochemical processes occurring at the interface of dissimilar materials during explosive welding have not yet been fully understood and continue to be the subject of ongoing investigation (Mashimo & Huang, 1999; Kan, Son & Hon, 2017). The ability of plastic deformation waves to propagate both through grain interiors and along grain boundaries, as well as across the interfaces of dissimilar metals, may contribute to the enhancement of the mechanical properties of composite materials (Deribas, 1980). The mechanisms and characteristics of plastic deformation wave propagation have been extensively analyzed in the works of V. E. Panin, who demonstrated their important role in the evolution of material structure and deformation behavior under nonequilibrium loading conditions (Panin, Egorushkin & Panin, 2012; Panin & Egorushkin, 2013).

The objective of the present work was to investigate the structural features of deformation localization regions in a steel 20–M1 copper–L80 brass multilayer composite produced by explosive welding.

The study focused on the analysis of microstructural evolution, phase and chemical composition, and microhardness variations throughout the cross-section of the multilayer material, with the aim of elucidating the relationships among these characteristics.

MATERIALS AND METHODS

The initial materials used for the fabrication of the layered composite were plates of 20 steel, M1 copper, and L80 brass with thicknesses of 18 mm, 6 mm, and 4 mm, respectively. Ammonite 6ZhV was employed as the explosive material. During the welding process, the copper and brass plates were bonded to a horizontally positioned steel plate using an angular explosive welding configuration. This arrangement enabled the formation of a multilayer steel–copper–brass composite through high-velocity impact and subsequent metallurgical bonding at the interfaces between the dissimilar materials (Mali & Teslenko, 2002; Mali et al., 2017). The impact angle was $\gamma = 6°$. The estimated velocity of explosive welding is Vk = 2500 m/s (contact velocity) and V_s = 260 m/s (impact velocity).

After fabrication of the layered composite specimens, metallographic, X-ray diffraction, and electron microprobe analyses were performed to characterize their microstructure, phase composition, and elemental distribution. These investigations were conducted to identify the structural features and phase constituents formed within the composite during the explosive welding process.

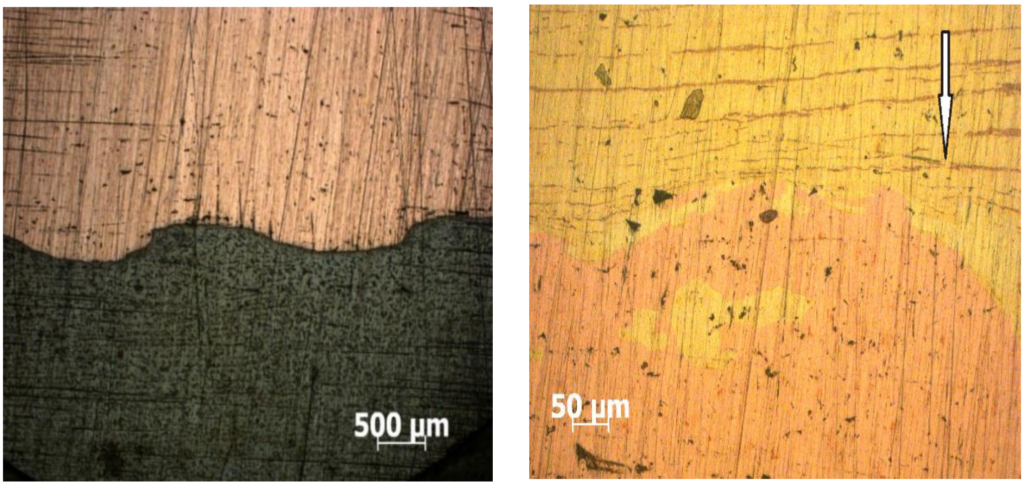
RESULTS AND DISCUSSION

Explosive welding of brass, copper, and steel was found to produce characteristic wavy interfacial boundaries between the bonded layers (Fig. 1).

Scanning electron microscopy (SEM) combined with microanalytical investigations revealed the formation of concentration-transition zones at the interfaces. Localized fluctuations in zinc concentration were detected in regions adjacent to the brass–copper interface, indicating the occurrence of intensive elemental redistribution during the welding process. These concentration gradients suggest enhanced mass transport and interfacial mixing under the extreme conditions generated by explosive welding.

Periodic row-like structures elongated in a direction perpendicular to the deformation axis were observed within the brass layer (Fig. 1,b). These features may be associated with the formation of newly developed phases. As demonstrated below by X-ray diffraction analysis, a nonequilibrium γ-brass phase enriched in zinc was detected in the L80 alloy despite being absent from its equilibrium phase composition. This observation suggests that plastic deformation was accompanied by anomalously rapid mass transport of copper from the brass layer toward the adjacent copper layer of the composite.

The spatial distribution of structural heterogeneities in the brass region directly adjacent to the copper layer indicates that mass transport occurred in a wave-like manner. This process manifested itself through the formation of successive transverse rows of structural features regularly arranged along the transition zone. Notably, the spacing between these structures decreases with decreasing distance to the copper–brass interface. Such behavior is consistent with the concept of wave-driven mass transfer and supports the existence of localized deformation waves governing material redistribution in the interfacial region (Panin & Egorushkin, 2013).



a *b*

Figure 1. Microstructure of the contact zones of the composite material:
a – steel 20 – copper M1; b – copper M1 – brass L80

Note – compiled by the authors based on the authors' experimental data.

The observed string-like structure appears to be a product of self-organization processes occurring during the propagation of shock waves. In irreversible systems, self-organization manifests through the spontaneous formation of ordered structures when the system reaches critical conditions. At these critical parameters, the initially stable state becomes structurally unstable, leading to the emergence of bifurcations and the development of new structural configurations. Under the extreme nonequilibrium conditions generated by shock-wave loading, such bifurcation phenomena can promote the formation of periodically arranged string-like structures and other dissipative patterns within the material (see arrow in Fig. 1, b) (Mali & Teslenko, 2002).

The observed string-like structure is likely a consequence of self-organization processes occurring during shock-wave propagation. In nonequilibrium systems, self-organization is manifested through the spontaneous emergence of ordered patterns when critical conditions are reached. At these critical thresholds, the initially stable state loses its stability, giving rise to bifurcation phenomena and the formation of new structural configurations. Under the extreme nonequilibrium conditions associated with shock-wave loading, such bifurcation processes may facilitate the development of periodically arranged string-like structures and other dissipative patterns within the material. These features can be regarded as manifestations of the system's tendency toward structural ordering during its evolution far from thermodynamic equilibrium.

During X-ray diffraction measurements, the incident beam was initially focused on the steel–copper interface and, after acquisition of the diffraction pattern, was subsequently shifted to the copper–brass interface region (Fig. 2). The presence of peaks corresponding to a zinc-containing phase in the diffraction pattern obtained from the steel–copper interaction zone may be attributed to limited accuracy in beam positioning, resulting in partial overlap with the adjacent copper–brass interface.

The occurrence of a nonequilibrium iron phase with a face-centered cubic (FCC) crystal structure in the copper–steel contact region has also been reported in previous studies involving severe joint plastic deformation of these metals (Kveglis et al., 2016). The stabilization of this phase under ambient pressure and room-temperature conditions is believed to result from the partial dissolution of copper in iron, which alters the phase stability and promotes the retention of the FCC structure.

A notable finding of the present study is the detection of the nonequilibrium Cu_5Zn_8 phase (γ-phase) (Fig. 2). According to the Cu–Zn phase diagram, L80 brass is expected to contain only the α-phase under equilibrium conditions. However, following explosive welding, the γ-phase—typically characteristic of brasses with a substantially higher zinc content—was also identified. The appearance of this phase as a result of intense plastic deformation provides evidence for anomalously rapid mass transport of alloying elements during the explosive welding process. The formation of the Cu_5Zn_8 phase indicates that local compositional redistribution occurred under highly nonequilibrium conditions, leading to the stabilization of phase constituents that would not be expected in the initial alloy system under equilibrium thermodynamic conditions.

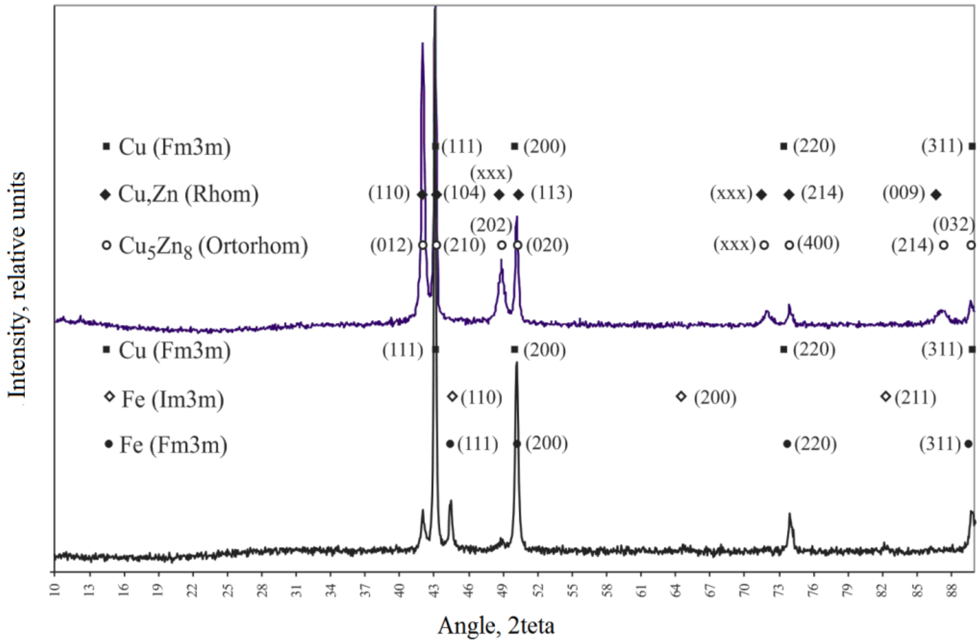


Figure 2. X-ray diffraction spectra recorded from the steel–copper contact zone (bottom) and the copper–brass contact zone (top).

Note – compiled by the authors based on the authors' experimental data.

The anomalous mass transport observed in the present experiments can be explained by the formation of interstitial bifurcation structural states generated during plastic deformation (Panin & Egorushkin, 2015). Distortion of the crystal lattice under deformation leads to the creation of excess free volume and to a redistribution of the electron density within localized regions of the material. These nonequilibrium conditions facilitate the formation of metastable phases that are not expected under equilibrium thermodynamic conditions. In particular, plastic deformation may promote the formation of the Hume–Rothery electronic phase Cu_5Zn_8, which is characterized by increased hardness. The appearance of this phase provides additional evidence for the significant structural and compositional rearrangements occurring during explosive welding and supports the proposed mechanism of deformation-induced anomalous mass transport (Safari, Khosroshahi & Zolriasatein, 2017; Degtyareva, 2005).

A PMT-3M microhardness tester (Fig. 3) was used to study the microhardness of the original sample. Microhardness measurements were performed using a Vickers diamond indenter. Indentations were made across the entire cross-section of the specimen at intervals of

100 μm under a load of 20 g, beginning in the brass layer and extending through the copper layer to the steel substrate.

As shown in Fig. 3, copper exhibited the lowest microhardness among the three constituent materials. Following explosive welding, its hardness remained nearly unchanged, and X-ray phase analysis did not reveal the formation of any new phases within the copper layer. This observation suggests that strengthening mechanisms unrelated to phase transformations, including deformation-induced relaxation processes, contributed only marginally to the hardening of this region. In contrast, the average hardness of the steel layer increased by approximately 27% relative to its undeformed state. The abrupt fluctuations observed in the microhardness profile may be attributed to the indenter penetrating locally harder microstructural constituents. In 20 steel, such regions are likely associated with cementite-containing areas. The overall increase in the average microhardness of the steel section may be explained by the formation of localized microvolumes possessing an austenitic structure within the matrix. Considering the observed changes in phase composition, it can be concluded that explosive deformation has a pronounced effect on the microstructural evolution and mechanical properties of the composite constituents. The formation of nonequilibrium phases and associated structural transformations plays a significant role in the strengthening behavior of the multilayer steel–copper–brass composite.

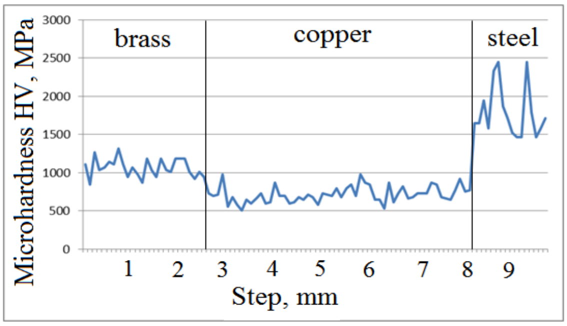


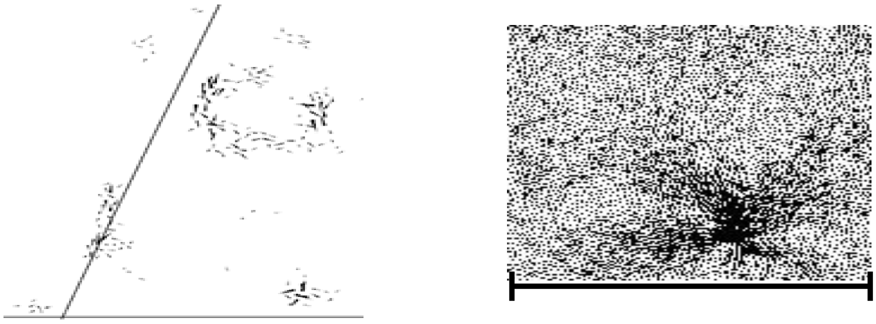
Figure 3. Variation of microhardness across the cross-section of the L80 brass–M1 copper–20 steel multilayer composite

Note – compiled by the authors based on the authors' experimental data.

According to Gilman (Gilman, 2003), the general mechanism of mechanochemical reactions can be interpreted within the framework of molecular orbital theory. Mechanical deformation increases the energy of bonding orbitals while simultaneously lowering the energy of antibonding orbitals. As a result, the energy gap between these states decreases, leading to destabilization of the atomic bonding system. When this energy gap approaches zero, bonding electrons become delocalized because occupation of antibonding states no longer requires additional energy. Under such conditions, the activation energy of a chemical reaction may effectively vanish. However, the nature of the reaction products is determined not only by the activation energy but also by geometric factors. These factors are governed by interatomic distances and the spatial orientation of chemical bonds, including the angles between bond directions. Consequently, the structural outcome of a mechanochemical transformation depends on both the energetic state of the system and the geometrical arrangement of atoms during deformation.

> It is now well established (Boldyrev, 2002) that a characteristic feature of solid-state reaction mechanisms is the increase in crystal lattice energy associated with the generation of excess free volume. Mechanical alloying has been shown to promote the redistribution and enhancement of electron density between atoms of the constituent elements, thereby increasing

their chemical reactivity. A similar mechanism, proposed by (Guzev & Dmitriev, 2013), is closely related to the development of crystal lattice curvature during plastic deformation. Such lattice distortions create nonequilibrium structural states that facilitate atomic rearrangement, enhance mass transport processes, and promote the formation of new phases under deformation-induced conditions.



a **b**

Figure 4. The "spindle" model

Note – compiled by the authors based on the authors' experimental data.

Figure 4 illustrates the stress field distribution obtained from molecular dynamics calculations. (Langer & Lemaitre, 2004).

a) The line indicates the direction of the applied load axis and the displacement of atoms around this axis,

b) Schematic representation of the elastic stress field distribution obtained by molecular dynamics simulation (Langer & Lemaitre, 2004).

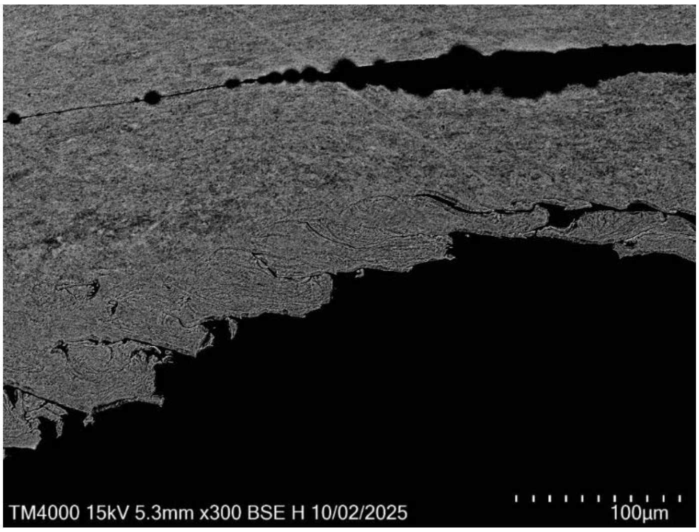


Figure 5. Electron microscopic image of a fragment of the flaring zone of a copper sample subjected to impact loading during explosion welding; a dark track and a cavity formed by the shock wave are visible

Note – compiled by the authors based on the authors' experimental data

Figure 5 shows an electron microscopic image of a fragment of the flaring zone of a copper sample subjected to impact loading during explosion welding; a dark track and a cavity formed by the shock wave are visible.

In addition to the large cavity, small round cavities located at different distances from each other are visible along the track. Under explosive welding conditions, high pressure develops in localized areas. Evolution of the structural and phase states of a condensed medium subjected to external mechanical loading. In Fig. 6, labels 1 and 1′ indicate gas-filled pores, whereas 2 and 2′ correspond to liquid-filled pores. T_3 denotes the triple equilibrium point of the solid sol, liquid (L), and gaseous phases, and $T_{(C)}$ is the critical temperature.

In Figure 5, the edge shape of the samples subjected to explosive deformation has the appearance of a fractal structure or viscous fingers. Figure 7 shows the calculated pattern of the chaotic growth of "viscous fingers" in Hele-Shaw cells as a function of time from top to bottom and left to right. The width of the "viscous fingers" is along the x-axis, and the length along the y-axis.

Figure 8 shows a Hele-Shaw experiment illustrating the formation and evolution of the hydrodynamic structure (Mironova, 2008).

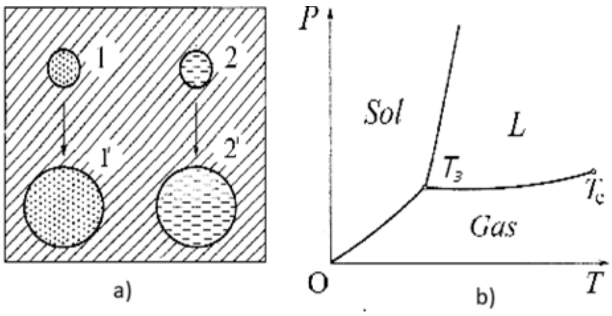


Figure 6. Evolution of structural and phase states in a condensed medium subjected to external mechanical loading: a – correlation between the development of continuity defects and transformations of the material's aggregate state; b – equilibrium phase diagram of the material under compressive stress conditions.

Note – compiled by the authors based on the authors' experimental data

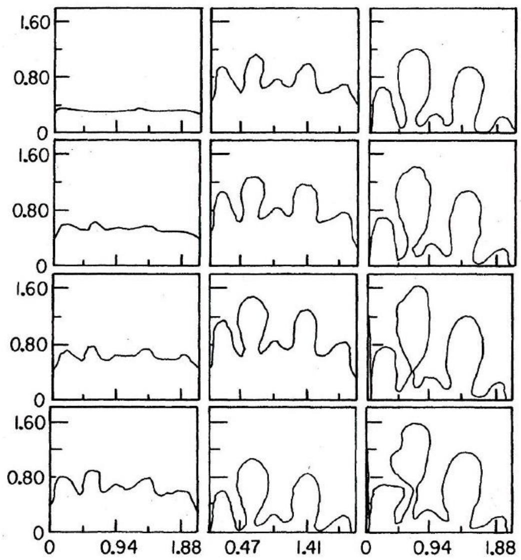


Figure 7. Pattern of chaotic growth of "viscous fingers" in Hele-Shau cells depending on time from top to bottom and from left to right. Along the x-axis is the width, along the y-axis is the length of the "viscous fingers", expressed in inches (Mironova, 2008).

Note – compiled by the authors based on the authors' experimental data.

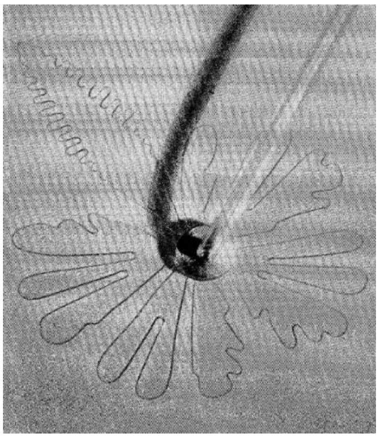


Figure 8. Hele-Shaw experiment illustrating the formation and evolution of a hydrodynamic structure (Mironova, 2008).
Note – compiled by the authors based on the authors' experimental data.

DISCUSSION OF RESULTS

The effect of displacement of atoms in solids over macroscopic distances in an extremely short time is well known, if we compare this phenomenon with diffusion (Noskov, 2018). It was called anomalous mass transfer due to the ultra-high migration rates of atoms, sometimes exceeding the mobility in liquid metals. It has been established that this effect can occur under various types of external loading, including both elastic and plastic deformation. Under conditions of nonlinear plastic deformation, particularly when deformation becomes localized within specific regions of a specimen, the resulting nonequilibrium state provides the necessary thermodynamic driving force for accelerated mass transport (Boldyrev, 2006). In deformation-induced mass transfer processes, a key role is played by the curvature of the crystal lattice and the emergence of new admissible structural states. These deformation-generated configurations facilitate atomic redistribution and contribute to the enhanced mobility of matter observed under intense mechanical loading conditions (Noskov, 2018).

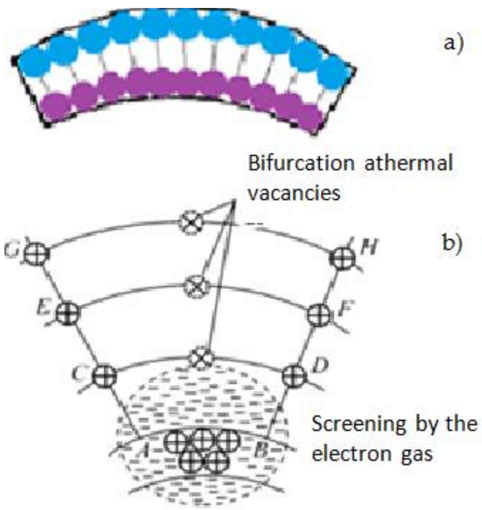


Figure 9. Schematic illustration of metastable bifurcation structural states (MBSS) in locally curved crystal lattices: a – lattice curvature generated by external mechanical loading at the interface of dissimilar metals; b – formation of interstitial bifurcation vacancy states within regions of lattice curvature, promoting increased atomic solubility and mass transport
Note – compiled by the authors based on the authors' experimental data

The mutual penetration of dissimilar atoms can lead both to changes in deformation behavior, known as the Rebinder effect, and to the initiation of chemical reactions followed by the formation of reaction products and new phases (Panin & Egorushkin, 2015).

Unlike conventional diffusion, which is driven primarily by concentration gradients, this transport mechanism is commonly referred to as deformation-induced atomic mixing or ballistic diffusion. In such processes, atomic redistribution is governed by intense mechanical deformation and the generation of nonequilibrium structural states rather than by thermally activated diffusion alone. Despite extensive research, there is still no universally accepted explanation of the underlying mechanism responsible for deformation-induced atomic mixing. Various models have been proposed, emphasizing the roles of lattice defects, localized plastic flow, crystal lattice curvature, and nonequilibrium atomic configurations in facilitating the accelerated transport of atoms under severe deformation conditions (Panin & Egorushkin, 2015).

According to the model proposed by (Panin & Egorushkin, 2015), the application of an external load to the interface between two dissimilar materials results in the modulation of normal and shear stresses, producing alternating regions of tension and compression (Fig. 9). This stress modulation generates zones of crystal lattice curvature at the interface, where regions with increased and decreased interatomic spacings become coupled.

Anomalous mass transport may be facilitated by interstitial bifurcation structural states (IBSS), which can be regarded as athermal vacancy-like defects formed within regions of localized crystal lattice curvature. The IBSS concept was introduced by (Panin & Egorushkin, 2015) to explain accelerated atomic transport under deformation conditions. Mechanical stresses create lattice-curvature zones in which enlarged interatomic distances are coupled, leading to a redistribution of the electron density. Within these regions, increased interionic spacings give rise to athermal vacancy states that are absent in an equilibrium crystal structure. The presence of IBSS significantly enhances the mutual solubility of dissimilar metals and promotes the rapid formation of metastable phases and atomically ordered structures. As a result, structural and phase transformations that would normally require prolonged diffusion times can occur within extremely short time intervals under severe deformation conditions.

CONCLUSIONS

The occurrence of abnormally rapid mass transfer and the formation of these phases during plastic deformation is confirmed by studies conducted using optical and electron microscopes and microhardness measurements.

Under the nonequilibrium conditions associated with composite fabrication, metastable phases and solid solutions can form that are absent from the equilibrium phase diagram. Crystal lattice distortion occurs over multiple length scales: at the macroscopic level, it is manifested by the wavy morphology of the copper–molybdenum interface; at the mesoscale, by the distortion of individual grain shapes; and at the atomic-crystalline level, by the distortion of atomic planes.At the atomic scale, the high energy-density gradients generated within localized regions give rise to bifurcation structural states. These nonequilibrium states facilitate the local formation of solid solutions between components that are mutually insoluble under equilibrium conditions. They may also promote the emergence of complex atomic arrangements, including icosahedral configurations, which are characteristic of metastable structural states. The formation of such structures provides further evidence of the profound influence of severe deformation and nonequilibrium processes on phase evolution and atomic redistribution in composite materials.

1. A layered composite material consisting of 20 steel, M1 copper, and L80 brass was successfully fabricated by explosive welding. The results demonstrate that mechanochemical interactions occurring during the explosive welding process lead to the formation of reaction products in the contact regions in the form of both equilibrium and nonequilibrium phases. These

phase transformations are associated with the extreme nonequilibrium conditions generated during high-velocity impact and play a significant role in determining the structural and mechanical properties of the resulting multilayer composite.

2. Analysis of the X-ray diffraction patterns revealed the presence of both equilibrium and nonequilibrium phases in the interfacial regions. At the copper–brass interface, equilibrium phases were identified together with the nonequilibrium Cu_5Zn_8 electronic phase, which is not expected in L80 brass under equilibrium conditions. At the copper–steel interface, equilibrium copper and α-iron phases were detected, along with the nonequilibrium γ-iron phase.

3. The structural transformations observed in the contact zones of the composite layers are attributed to anomalously rapid mass transport of copper into iron and zinc from brass into copper. This process is associated with the formation of interstitial bifurcation structural states in regions of crystal lattice curvature. The observed microstructural features further indicate that the mechanochemical processes proceed in a wave-like manner.

4. The results demonstrate that the increase in microhardness induced by explosive plastic deformation is primarily associated with changes in phase composition rather than with purely deformation-related structural effects. The contribution of deformation strengthening appears to be reduced due to relaxation processes, whereas phase transformations play the dominant role in the hardening of the composite material.

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DATA AVAILABILITY STATEMENT: The data supporting the findings of this technical study are available from the corresponding author upon reasonable request; alternatively.

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REFERENCES

Degtyareva, V., Degtyareva, O., Sakharov, M., & Przemyslaw, D. (2005). Stability of Hume-Rothery phases in Cu-Zn alloys at pressures up to 50 GPa. Journal of Physics: Condensed Matter, 17, 7955–7962. https://surl.li/lsdcyh

Gilman, J. J. (2003). Electronic basis of the strength of materials. Cambridge University Press. https://doi.org/10.1063/1.1801871

Kaloshkin, S. D., Tomilin, I. A., Andrianov, G. A., Baldokhin, U. V., & Shelekhov, E. V. (1997). Phase transformations and hyperfine interactions in mechanically alloyed Fe-Cu solid solutions. Materials Science Forum, 235–238, 565–570. https://www.scientific.net/MSF.235-238.565

Langer, J. S., & Lemaitre, A. (2004). Dynamic model of super-Arrhenius relaxation in glassy materials. arXiv: cond-mat/0411038v1. https://doi.org/10.1103/physrevlett.94.175701

Mali, V. I., Kurguzov, V. D., Esikov, M. A., Bataev, A. A., Maliutina, I. N., Bataev, I. A., & Lozhkin, V. S. (2017). Microstructure and mechanical properties of Ti/Ta/Cu/Ni alloy laminate composite materials produced by explosive welding. The International Journal of Advanced Manufacturing Technology, 93(9–12), 4285–4294. https://link.springer.com/article/10.1007/s00170-017-0887-8

Mashimo, T., & Huang, X. S. (1999). Metastable BCC and FCC alloy bulk bodies in Fe-Cu system prepared by mechanical alloying and shock compression. Journal of Alloys and Compounds, 288, 299–305. https://doi.org/10.1016/S0925-8388(99)00108-5

Safari, F., Khosroshahi, R., & Zolriasatein, A. (2017). Wear behavior of copper matrix composites reinforced by γ-Cu5Zn8 nanoparticles. Powder Technology, 547–559. https://doi.org/10.1016/j.powtec.2017.06.032

Болдырев, В. В. (2002). Об истории развития механохимии в Сибири. Химия в интересах устойчивого развития, 10, 3–12. https://www.sibran.ru/upload/iblock/bd8/bd874ec08851b6fcaab332bf52b2c237.pdf // Boldyrev, V. V. (2002). Ob istorii razvitiya mekhanokhimii v Sibiri [On the history of the development of mechanochemistry in Siberia]. Khimiya v interesakh ustoichivogo razvitiya [Chemistry for Sustainable Development], 10, 3–12. https://www.sibran.ru/upload/iblock/bd8/bd874ec08851b6fcaab332bf52b2c237.pdf (In Russ.)

Болдырев, В. В. (2006). Механохимия и механическая активация твёрдых веществ. Успехи химии, 75(3), 203–216. https://www.uspkhim.ru/RCR1205pdf // Boldyrev, V. V. (2006). Mekhanokhimiya i mekhanicheskaya aktivatsiya tverdykh veshchestv [Mechanochemistry and mechanical activation of solids]. Uspekhi khimii [Russian Chemical Reviews], 75(3), 203–216. https://www.uspkhim.ru/RCR1205pdf (In Russ.)

Бутягин, П. Ю. (1991). Физические и химические пути релаксации упругой энергии в твердых телах. Механохимические реакции в двухкомпонентных системах. В Механохимический синтез в неорганической химии (с. 32–52). Новосибирск: Наука. https://www.uspkhim.ru/RCR3138pdf // Butyagin, P. Yu. (1991). Fizicheskie i khimicheskie puti relaksatsii uprugoi energii v tverdykh telakh. Mekhanokhimicheskie reaktsii v dvukhkomponentnykh sistemakh [Physical and chemical pathways of elastic energy relaxation in solids. Mechanochemical reactions in two-component systems]. In Mekhanokhimicheskii sintez v neorganicheskoi khimii [Mechanochemical synthesis in inorganic chemistry] (pp. 32–52). Nauka. https://www.uspkhim.ru/RCR3138pdf (In Russ.)

Вайнерман, А. Е., & Пичужкин, С. А. (2002). Сварка меди и сплавов на ее основе со сталями: обзор литературы. Вопросы материаловедения, 4(32), 52–65. https://surl.lu/yxvlin // Vainerman, A. E., & Pichuzhkin, S. A. (2002). Svarka medi i splavov na ee osnove so stalyami: obzor literatury [Welding of copper and copper-based alloys with steels: A literature review]. Voprosy materialovedeniya [Materials Science Issues], 4(32), 52–65. https://surl.lu/yxvlin (In Russ.)

Гузев, М. А., & Дмитриев, А. А. (2013). Бифуркационное поведение потенциальной энергии системы частиц. Физическая мезомеханика, 16(3), 27–33. https://cyberleninka.ru/article/n/bifurkatsionnoe-povedenie-potentsialnoy-energii-sistemy-chastits/pdf // Guzev, M. A., & Dmitriev, A. A. (2013). Bifurkatsionnoe povedenie potentsialnoi energii sistemy chastits [Bifurcation behavior of the potential energy of a particle system]. Fizicheskaya mezomekhanika [Physical Mesomechanics], 16(3), 27–33. https://cyberleninka.ru/article/n/bifurkatsionnoe-povedenie-potentsialnoy-energii-sistemy-chastits/pdf (In Russ.)

Кан, К. Т., Сон, Ч. С., & Хон, С. И. (2017). Влияние температуры процесса соединения прокаткой на прочность и удельную электропроводимость получаемого композита α-латунь/сплав Cu-1 вес. % Cr/α-латунь. Физика металлов и металловедение, 118(2), 200–208. https://dokumen.pub/9785763842258.html // Kan, K. T., Son, Ch. S., & Khon, S. I.

(2017). Vliyanie temperatury protsessa soedineniya prokatkoi na prochnost i udelnuyu elektroprovodimost poluchaemogo kompozita α-latun/splav Cu-1 ves. % Cr/α-latun [Influence of the roll-bonding process temperature on the strength and specific electrical conductivity of the α-brass/Cu-1 wt.% Cr alloy/α-brass composite]. Fizika metallov i metallovedenie [Physics of Metals and Metallography], 118(2), 200–208. https://dokumen.pub/9785763842258.html (In Russ.)

Квеглис, Л. И., Носков, Ф. М., Калитова, А. А., & Абкарян, А. А. (2016). Структурообразование в системе сталь-медь. Химия в интересах устойчивого развития, 24(2), 229–237. https://doi.org/10.15372/khur20160216 // Kveglis, L. I., Noskov, F. M., Kalitova, A. A., & Abkaryan, A. A. (2016). Strukturoobrazovanie v sisteme stal-med [Structure formation in the steel-copper system]. Khimiya v interesakh ustoichivogo razvitiya [Chemistry for Sustainable Development], 24(2), 229–237. https://doi.org/10.15372/khur20160216 (In Russ.)

Мали, В.И., & Тесленко, Т.С. (2002). Структура и свойства взрывных компактов медь-молибден. Физика горения и взрыва, 38(4), 106–111. https://www.dissercat.com/content/zakonomernosti-formirovaniya-fazovogo-sostava-i-struktury-kompozitsionnykh-materialov-i-pokr // Mali, V. I., & Teslenko, T. S. (2002). Struktura i svoistva vzryvnykh kompaktov med-molibden [Structure and properties of explosive copper-molybdenum compacts]. Fizika goreniya i vzryva [Combustion, Explosion, and Shock Waves], 38(4), 106–111. https://www.dissercat.com/content/zakonomernosti-formirovaniya-fazovogo-sostava-i-struktury-kompozitsionnykh-materialov-i-pokr (In Russ.)

Миронова, О. А. (2008). Характеристики ускоренного массопереноса при ударном сжатии металлов с кубической решеткой [Диссертация на соискание ученой степени кандидата физико-математических наук, Москва]. https://www.dissercat.com/content/-kharakteristiki-uskorennogo-massoperenosa-pri-udarnom-szhatii-metallov-s-kubicheskoi-reshetk // Mironova, O. A. (2008). Kharakteristiki uskorennogo massoperenosa pri udarnom szhatii metallov s kubicheskoi reshetkoi [Characteristics of accelerated mass transfer during shock compression of metals with a cubic lattice] [Dissertation for the degree of Candidate of Physical and Mathematical Sciences, Moscow]. https://www.dissercat.com/content/kharakteristiki-uskorennogo-massoperenosa-pri-udarnom-szhatii-metallov-s-kubicheskoi-reshetk (In Russ.)

Носков, Ф.М. (2018). Структурообразование зон локализации пластической деформации в сплавах 3d-переходных металлов как результат быстропротекающих процессов [Диссертация на соискание степени доктора технических наук, Новокузнецк]. http://www.dslib.net/kondensat/strukturoobrazovanie-zon-lokalizacii-plasticheskoj-deformacii-v-splavah-3d.html // Noskov, F.M. (2018). Strukturoobrazovanie zon lokalizatsii plasticheskoi deformatsii v splavakh 3d-perekhodnykh metallov kak rezultat bystroprotekayushchikh protsessov [Structure formation of plastic deformation localization zones in alloys of 3d transition metals as a result of fast processes] [Dissertation for the degree of Doctor of Technical Sciences, Novokuznetsk]. http://www.dslib.net/kondensat/strukturoobrazovanie-zon-lokalizacii-plasticheskoj-deformacii-v-splavah-3d.html (In Russ.)

Панин, В.Е., & Егорушкин, В.Е. (2013). Солитоны кривизны как обобщенные волновые структурные носители пластической деформации и разрушения. Физическая мезомеханика, 16(3), 7–26. https://cyberleninka.ru/article/n/solitony-krivizny-kak-obobschennye-volnovye-strukturnye-nositeli-plasticheskoy-deformatsii-i-razrusheniya // Panin, V. E., & Egorushkin, V. E. (2013). Solitony krivizny kak obobshchennye volnovye strukturnye nositeli plasticheskoi deformatsii i razrusheniya [Curvature solitons as generalized wave structural carriers of plastic deformation and fracture]. Fizicheskaya mezomekhanika [Physical Mesomechanics], 16(3), 7–26. https://cyberleninka.ru/-article/n/solitony-krivizny-kak-obobschennye-volnovye-strukturnye-nositeli-plastiches-koy-deformatsii-i-razrusheniya (In Russ.)

Панин, В. Е., & Егорушкин, В. Е. (2015). Основы физической мезомеханики пластической деформации и разрушения твердых тел как нелинейных иерархически организованных систем. Физическая мезомеханика, 18(5), 100–113. https://cyberleninka.ru/article/n/17177468.pdf // Panin, V. E., & Egorushkin, V. E. (2015). Osnovy fizicheskoi mezomekhaniki plasticheskoi deformatsii i razrusheniya tverdykh tel kak nelineinykh ierarkhicheski organizovannykh sistem [Fundamentals of physical mesomechanics of plastic deformation and fracture of solids as nonlinear hierarchically organized systems]. Fizicheskaya mezomekhanika [Physical Mesomechanics], 18(5), 100–113. https://cyberleninka.ru/article/n/17177468.pdf (In Russ.)

Панин, В.Е., Егорушкин, В.Е., & Панин, А.В. (2012). Нелинейные волновые процессы в деформируемом твердом теле как многоуровневой иерархически организованной системе. Успехи физических наук, 182(12), 1351–1357. https://doi.org/10.3367/-UFNr.0182.201212i.1351 // Panin, V.E., Egorushkin, V.E., & Panin, A.V. (2012). Nelineinye volnovye protsessy v deformiruemom tverdom tele kak mnogourovnevoi ierarkhicheski organizovannoi sisteme [Nonlinear wave processes in a deformable solid as a multilevel hierarchically organized system]. Uspekhi fizicheskikh nauk [Physics-Uspekhi], 182(12), 1351–1357. https://doi.org/10.3367/UFNr.0182.201212i.1351 (In Russ.)

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