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Effect of ultrasonic treatment on structural transformations and mechanical behaviour of amorphous alloys (REVIEW)

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Abstract: The wide application of amorphous alloys is complicated by a narrow range of their thermal stability, embrittlement at elevated temperatures, difficult machinability, and low tensile plasticity. Ultrasonic treatment is an innovative method for solving these problems. Integration of ultrasonic technology into the technological chain can contribute to the improvement of the operational property of amorphous alloys, the manufacture of parts from them at different scale levels, and high-quality joining with other materials. The effect of ultrasonic vibrations on structural transformations and mechanical behaviour of amorphous alloys is not completely understood. The lack of an integrated scientific basis for the physical processes and accompanying effects in amorphous alloys under ultrasonic excitation prevents the development of the corresponding technology and optimization of its modes. Over the past decade, researchers have proposed various methods of ultrasonic treatment of amorphous alloys to improve their formability, achieve a balance of plasticity and strength, and consolidate with each other and with metals. In addition, certain ideas have been developed about their structure rejuvenation and the possibilities of transformation them to a partially nanocrystalline state under the action of ultrasound. To summarise these developments, the systematic discussion on features, parameters, and modes of ultrasonic treatment applied to ribbon and bulk amorphous alloys to improve their structure-sensitive properties are provided in this review. On this basis, the limitations of current study are discussed. The most promising applications of ultrasonic technologies for rapidly melt-quenched alloys in the near future include: their additive manufacturing, creation of hybrid composites by ultrasonic welding, ultrasonic forming for manufacturing products of complex shapes and geometries, complex multi-stage processing to obtain a unique combination of properties (e.g., melt quenching → laser irradiation → ultrasonic stimulation). This review enhances the existing knowledge on ultrasonic control of the properties and structure of amorphous alloys and facilitates a fast references on this topic for researchers.

Keywords: amorphous alloy; ultrasonic treatment; structural transformations; mechanical behaviour; nanocrystal; structure rejuvenation; composite; plasticity; forming.

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INTRODUCTION

Amorphous alloys (AAs) produced by rapid melt quenching or by casting in a copper casting-mold (in the case of bulk amorphous alloys) have unique physical properties, which makes them very promising for many applications in such areas as energy production, electronics, catalysis, medicine, and the aerospace industry [1–3]. Due to their unusual structure with the absence of long-range order and structural defects such as dislocations and grain boundaries, amorphous alloys, compared to their crystalline counterparts, are characterised by an increased elastic limit, high strength, hardness, corrosion and wear resistance, catalytic activity, and some of them – by biocompatibility [4–6]. However, as a kind of metastable material, AAs transform into a more stable energy state under the action of applied stresses, high temperatures, or even under natural conditions. The phenomenon of "aging" of the structure may be accompanied by deterioration of properties. Moreover, amorphous alloys demonstrate almost zero tensile plasticity due to the propagation of main highly localised shear bands, which prevents their use as a structural material [7; 8]. In this regard, the close attention of material scientists is focused on the development of strategies for the structural rejuvenation of AAs, which will contribute to greater disordering of the amorphous matrix and, thus, effective softening [9]. On the other hand, the balance of strength and plasticity can be achieved by forming an optimal proportion of nanocrystals in the volume of AAs, which can prevent crack propagation and initiate an increase in the number of shear bands, due to which plastic deformation in amorphous alloys is realised [10–12]. Numerous approaches are used to modify the structure of AAs, overcome embrittlement, and improve their thermal stability: annealing and thermal cycling [13–15], electrostatic compression [16; 17], ion irradiation [18; 19], cold rolling [20; 21], and high-pressure torsion [22; 23]. However, these methods usually require a lot of experimental time and high costs, and some have limitations in sample size, which makes their application in production processes quite difficult. Therefore, there is an urgent need to develop an innovative, one-step, convenient approach to the processing of amorphous alloys. The method based on the use of ultrasonic (US) vibration energy with a frequency above 20 kHz is one of the promising methods for processing materials, characterised by ease of control and a fast response time [24–27]. It can directly introduce high energy into the glassy matrix, affecting the response of properties and complex physical processes, including glass transition, structural relaxation, crystallization, strengthening and plasticization mechanisms.

The purpose of this work is to analyse the world experience of using ultrasonic processing to control the structure and improve the properties of amorphous alloys, as well as to carry out technological operations with them.

METHODS

The search for relevant scientific papers related to the review topic covered the period from the moment of the first publication to the present day. The selection was carried out among papers of peer-reviewed journals, books, conference materials from reliable international abstracting and indexing databases Web of Science and Scopus. Moreover, in order to track current studies, the resources of the Russian Science Citation Index (RSCI) and the patent database of the Russian Federation were used.

The ranking of the found materials was carried out depending on the characteristics of the physical processes and phenomena occurring during ultrasonic treatment, as well as the achievement of specific practical goals. In accordance with this, three areas of research on amorphous alloys during ultrasonic modification were identified:

1) study of the processes of rejuvenation of their structure for the implementation of forming;

2) study of the processes of nanocrystallization of amorphous alloys for the best combination of strength and plasticity;

3) development of the methodology of ultrasonic soldering/welding for effective rapid connection of amorphous alloys with each other or with crystalline materials.

RESULTS

1. Retrospective analysis

When analysing literary sources in retrospect, it is important to note an important fact: the first publications on the use of ultrasonic excitation on amorphous alloys appeared in Russia. In 1992, scientists O.M. Smirnov and A.M. Glezer from the I.P. Bardin Central Research Institute of Ferrous Metallurgy in their paper [28], and a year later in their author's certificate [29], noted the effectiveness of ultrasonic treatment for improving the mechanical properties of Fe–Cr–B amorphous alloys ribbon. Only almost a decade later, in 2003, full-scale studies in this area were launched at the Universities of Osaka and Kagawa [30; 31]. At first, the response of elastic and inelastic properties of bulk zirconium-based $Zr_{55}Cu_{30}Ni_5Al_{10}$ AA under ultrasonic vibrations was studied, and the experiments were carried out in a very wide frequency range of 300–1500 kHz [30]. In 2005, the features of $Pd_{42.5}Ni_{7.5}Cu_{30}P_{20}$ AA crystallization were studied at frequencies of 0.35 MHz [31]. Then, Japanese researchers decided to test the possibility of joining amorphous alloys with each other using ultrasonic welding and in 2008 reported successful consolidation of $Zr_{55}Cu_{30}Ni_5Al_{10}$ using a combination of ultrasonic welding and slight heating (below the glass transition temperature) [32]. Several publications were enough to arouse interest in China and to seize the initiative in conducting fundamental research on the effect of ultrasonic stimulation on the structure and properties of amorphous alloys. Currently, Chinese research groups are the absolute leaders in this area. Attempts to study ultrasonic technologies as applied to amorphous alloys were also made in the USA [33], Belarus [34], Germany [35], and Ukraine [36–39], but only sporadically.

2. Structural rejuvenation

2.1. The problem of embrittlement and its solutions

It was found that metallic materials undergo significant softening accompanied by a decrease in strength under the influence of ultrasound (acoustoplasticity effect, or Blaha effect) [40; 41]. Based on these characteristics, the forming technology using ultrasonic vibration was developed. Brittleness remains one of the main disadvantages of amorphous alloys, preventing their wider application. During labour-intensive processes (irradiation, elastostatic loading, cryothermal cycling) when combating the loss of plasticity in AA, reverse relaxation inevitably intervenes, which weakens the effect of structural rejuvenation. Moreover, the rejuvenation mechanism itself is not completely clear. In order to find suitable solutions to the embrittlement problem, in studies in recent years, ultrasonic vibrations have been combined with the process of forming amorphous alloys.

In [42; 43], a significant improvement in the thermoplastic formability of bulk $Zr_{35}Ti_{30}Be_{26.75}Cu_{8.25}$ amorphous alloys was found when using ultrasonic vibrations and its positive correlation with the ultrasound amplitude. In [44], a method of compression using ultrasonic vibration was proposed. By the example of $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$ alloy, it was shown that this method can achieve rapid (in 10 s) structural rejuvenation, and the alloy itself becomes more heterogeneous with better ability to plastic deformation. Moreover, under ultrasonic compression, plastic deformation occurs on the fracture surface of the alloy, indicating that as the ultrasound amplitude gradually increases, the yield strength of the alloy decreases and the plasticity increases, which can significantly simplify the formability of the alloy at room temperature.

2.2. Physical aspects of the rejuvenation process and the accompanying response of mechanical properties

Fig. 1 shows schematically a multilevel landscape of potential energy illustrating the evolution of possible structural states of amorphous alloy. Energy wells and barriers control the thermodynamic stability of the material. The deepest minimum of energy corresponds to stable crystalline phases, and other energy minima represent some metastable glassy states (Fig. 1 a).

Rejuvenation is accompanied by an increase in potential energy and an increase in the free volume concentration. In turn, structural relaxation leads to a decrease in potential energy and a lower free volume content compared to the initial state of amorphous alloy (under conditions of ultrafast cooling during their production) [45]. Annihilation of free volume or loose packing regions during aging leads to the fact that AAs become even more brittle. However, when energy is introduced into amorphous alloy using ultrasonic vibrations at certain values of amplitude and exposure time, they are able to rejuvenate, since they acquire additional free volume and greater plasticity. During ultrasonic treatment, the combined effect of external applied elastic stress, internal converted heat and ultrasonic resonance of atoms can stimulate the movement of loosely packed atoms in the AA to a high-energy state, thereby causing the formation of other regions with free volume and rheological units to improve formability [44; 46].

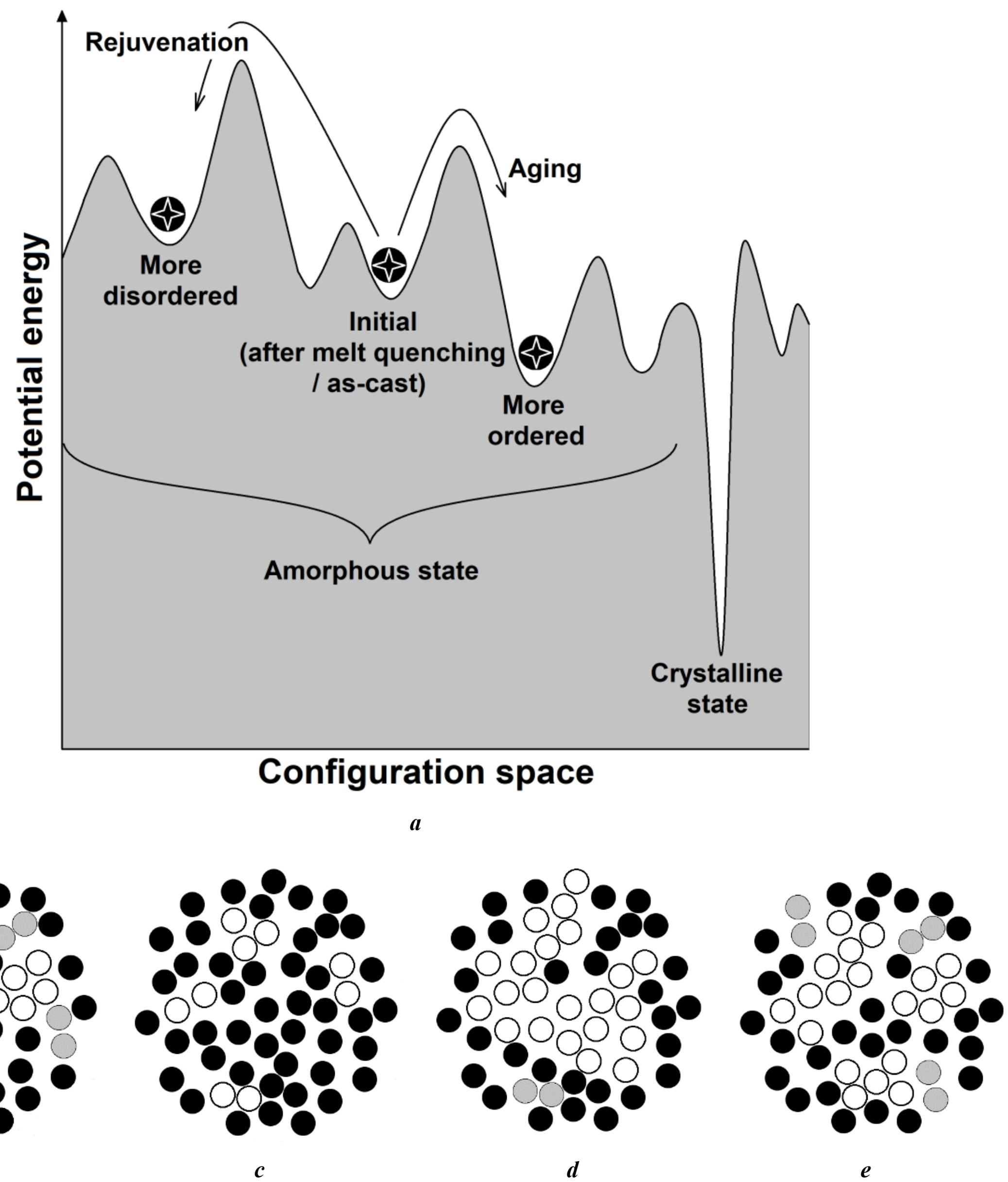

Fig. 1. *Schematic illustrations of the energy states of atoms in the potential landscape (**a**) and the structure evolution of amorphous alloys in initial state (**b**), during aging (**c**), during ultrasonic rejuvenation (**d**) and afterwards (**e**)*

Рис. 1. *Схематические иллюстрации энергетических состояний атомов в потенциальном ландшафте (**a**) и эволюции структуры аморфных сплавов в исходном состоянии (**b**), при старении (**c**), в процессе УЗ омоложения (**d**) и после него (**e**)*

In as-cast and melt-quenched amorphous alloys, reversible and irreversible β-relaxations can occur [47], the behaviour of which can be judged by the configurations of white and grey atoms in Fig. 1 b, respectively. With increasing aging time, the grey regions gradually become black, and the white ones are significantly compressed (Fig. 1 c). Under ultrasonic loading, the structure again becomes loosely packed (Fig. 1 d), so the set of highly mobile white atoms increases, and zones with grey atoms appear again after exposure to ultrasound (Fig. 1 e).

In [48], using atomistic modelling and evaluation of the nanomechanical characteristics of bulk $La_{55}Al_{25}Ni_5Cu_{10}Co_5$, $Pd_{40}Cu_{30}P_{20}Ni_{10}$ and $Zr_{35}Ti_{30}Cu_{8.25}Be_{26.75}$ amorphous alloys, evidence was provided that their significant plastic flow below the glass transition temperature under ultrasonic exposure is explained by dynamic inhomogeneity and cyclically induced atomic-scale expansions (liquefaction) in the amorphous alloys. This leads to significant rejuvenation and final "collapse" of the solid-like amorphous structure.

In [36; 37], the influence of preliminary ultrasonic treatment on the mechanical properties and structural features of bulk $Zr_{52.5}Ti_5Cu_{17.9}Ni_{14.6}Al_{10}$ and $Zr_{46.25}Cu_{45.25}Al_{7.5}Er_1$ amorphous alloys was studied using the acoustic emission method under uniaxial compression. The research results were interpreted within a polycluster model of the AA structure. The analysis of the obtained data allowed substantiating the mechanism of structural changes and a decrease in the strength of amorphous alloys as a result of alternating mechanical loading with an ultrasonic frequency of 20 kHz. The authors substantiated that the resistance to plastic deformation of amorphous alloys is determined by the strength of the intercluster boundaries, which are restructured and "softened" under the action of ultrasonic mechanical loading.

In [49; 50], the mechanical behaviour of $Pd_{40}Cu_{30}P_{20}Ni_{10}$ and $La_{55}Al_{25}Ni_5Cu_{10}Co_5$ amorphous alloys after ultrasonic vibrations was studied by the nanoindentation method. A noticeable softening after ultrasonic treatment was expressed as a decrease in hardness and elastic modulus – by ~25 and 40 %, respectively. It was found that flow defects with a shorter characteristic relaxation time, activated under loading with ultrasonic cycling, promote rapid diffusion of atoms with a low energy barrier. Ultimately, this leads to a noticeable creep displacement and, thus, to greater formability at ambient temperature.

A method for producing amorphous alloys was proposed, which included melting a metal blank in a crucible, melt quenching the on a rapidly rotating disk, but the nuance was that in order to increase the temperature range of plasticity, immediately after removing the ribbon, it was additionally subjected to ultrasonic treatment with an amplitude of alternating stresses [29]. In this case, the ratio of the amplitude of alternating stresses to the Young's modulus of the processed material should be within the range of $(0.135–0.48)\times10^{-3}$. This range was chosen so that the applied alternating stresses of ultrasonic frequency did not exceed the yield strength of the studied amorphous alloys, did not provoke their subsequent destruction, but contributed to the effective preservation of plasticity and a shift in the embrittlement threshold towards higher temperatures.

In the work [28], using the example of the $Fe_{70}Cr_{15}B_{15}$ AA, it was shown that, depending on the ultrasonic impact parameters, the critical temperature of amorphous alloy embrittlement can shift either upward or downward depending on the amplitude of the ultrasonic vibrations used.

The results of dilatometric studies in the work [38] show an increase in the temperature of crystallization of the $Fe_{76}Ni_4Si_{14}B_6$ AA by 30–50 K after different modes of ultrasonic treatment and the microhardness of the amorphous alloy decreases by 15 %. This indirectly confirms the fact that the percentage content of the crystalline phase in the alloy decreases due to a decrease in the size or dissolution of frozen crystallization centres in the amorphous alloy.

2.3. Ultrasonic assisted shear punching

Ma J. et al. used high-frequency vibrations for shear punching of templates, products from bulk and ribbon amorphous alloys of the following systems: Zr–Ti–Cu–Be, Fe–Si–B, La–Al–Ni–Cu–Co, La–Ni–Al, and Cu–Zr [51–53]. Fig. 2 shows a schematic representation of the experimental assembly for this technology.

Under the action of ultrasonic vibration of the punch, the plastic powder melts due to frictional heat generation and viscoelastic thermal effect and continues to flow downwards under the action of the extrusion of the ultrasonic head, plastically deforming the amorphous ribbon or plate. The disordered structure of the amorphous alloys helps them to soften in a localised area during high-frequency vibrations, which leads to low-stress deformations. For example, using ultrasonic vibrations and a molten plastic viscous medium, various forms of AA in the shape of the letters "B", "M", "G" and Chinese characters 工, 大 were produced on an area of 5 mm^2 [51]. In [54], to increase the plasticity of amorphous alloys, a method for their forming using ultrasonic vibrations in liquid media (fresh and sea water, alcohol) was proposed. In the process of this treatment, at low stress (300 MPa) and temperatures significantly below the glass transition temperature T_g, complex structures such as lattices, gear wheels and hexagons about 5 mm in size were successfully produced from AA in 1 s.

These fast ultrasonic forming methods (from milliseconds to several seconds) help to preserve the amorphous nature. They largely allow avoiding time-dependent crystallization and oxidation processes and thereby bypassing traditional heat treatment, as well as the risk of crystal growth. In order to prevent the AA relaxation, it is possible to adjust the ultrasonic thermal effect by controlling the amplitude and time under compression with ultrasonic vibration, and thereby effectively improve the mechanical properties of amorphous alloys.

Promising ultrasonic methods to improve the plasticity of amorphous alloys at room temperature (ultrasonic assisted shear punching and ultrasonic extrusion forming) can be applied to the rapid manufacture of macro-, micro-,

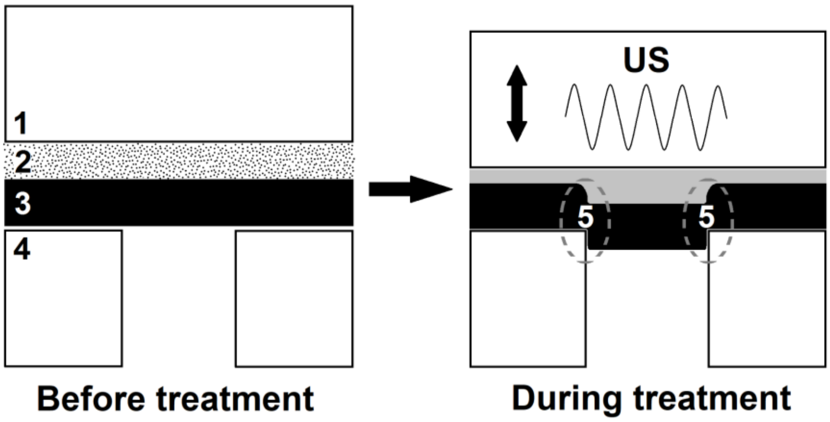

Fig. 2. *Schematic diagram of the ultrasonic assisted micro-shear punching set-up:*
1 – punch; 2 – polymer powder (e.g., ethylene vinyl acetate);
3 – amorphous alloy; 4 – mold cavity;
5 – softening zones in amorphous alloy (highlighted by dotted line)
Рис. 2. *Принципиальная схема установки для УЗ сдвиговой штамповки:*
1 – пуансон; 2 – полимерный порошок (например, этиленвинилацетат);
3 – аморфный сплав; 4 – пресс-форма с полостью;
5 – зоны размягчения в аморфном сплаве (выделены пунктиром)

nanoproducts and devices from amorphous alloys on the surface of metal materials. Forming of AA in liquids opens up exciting opportunities for application in aerospace, energy and marine engineering: in situ repair of ships and containers, polar construction, deep-sea exploration, providing valuable information and paving the way for future advances in underwater processing techniques.

3. Nanocrystallization

3.1. Methods for creating an amorphous-nanocrystalline state

When stretched, amorphous alloys demonstrate poor macroscopic plastic deformation at ambient temperature, which is a result of the formation of highly localised shear bands, as well as surface softening, which limits their wide application as construction materials [7; 8]. To solve this problem, methods have been proposed aimed at increasing the heterogeneity of AAs or creating a small number of micrometre-sized [55; 56] and nanosized crystals [57; 58] embedded in amorphous matrices: composition development [59], annealing treatment [60], nitrogen additives [61], and severe plastic deformation [62]. The scientific concept of the listed technologies is to activate the nucleation of shear bands or prevent the propagation of shear bands. Ultrasound induces strong forced vibration action of atoms and/or molecules and nonlinear effects such as acoustic cavitation and acoustic flow, which change the microstructure and properties of various materials. In particular, the introduction of ultrasonic energy into AAs can increase their heterogeneity in atomic rearrangement and even lead to the formation of crystallites. Ultrasonic resonance can modulate the inhomogeneity of AAs and improve the mechanical properties of rejuvenated zones [63]. Ultrasonic vibrations of MHz frequency lead to partial crystallization of bulk Pd-based AA when it is annealed below the glass transition temperature [31]. In [33], the ultrasonic surface modification method was used to treat $Zr_{44}Ti_{11}Cu_{10}Ni_{10}Be_{10}$ amorphous alloy and it was shown that its fracture strength and deformation were enhanced in a three-point bending experiment.

3.2. Balance of strength and plasticity

An urgent issue arises: can ultrasound overcome the dilemma of compromise between strength and plasticity in amorphous alloys? The introduction of a significant amount of free volume and a small amount of dispersed nanocrystals into AA by means of ultrasonic vibrations can effectively prevent the propagation and expansion of cracks during fracture, thereby improving their strength and plasticity at room temperature [64; 65]. The authors of [65] used intermittent high-frequency vibration loading to control the behaviour of shear deformation and atomic arrangement in bulk $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ AA. It was found that this method allowed increasing very quickly (in 4 s) the plasticity of the alloy (up to 5.3 %) and its strength (up to 2240 MPa) by increasing the content of free volume and forming $CuZr_2$ nanocrystals in the amorphous matrix. However, it was noted that with excess ultrasonic energy, there is a risk of transition from the plastic state to the brittle state if the volume fraction of nanocrystals exceeds the critical limit.

In work [64], amorphous Cu-based composites at room temperature were subjected to elastic preload from 250 to 1000 N and ultrasonic treatment with ultrasound amplitudes from 15 to 50 μm. It was shown that at low values of amplitudes and preloads, the free volume dominates, and nanocrystals do not precipitate. At low amplitudes / medium preloads or at medium amplitudes / low preloads, the free volume and nanocrystals coexist together as integral parts of the structure. At high values of amplitudes and loads, nanocrystals prevail, and the free volume content decreases sharply. Increasing the amplitude and decreasing the preload improves the efficiency of ultrasonic transmission.

In the work [66], 20 kHz ultrasonic excitation was applied to bulk $Zr_{46.75}Cu_{46.75}Al_{6.5}$ amorphous alloy and its influence on the microstructure evolution and mechanical properties was studied. It is found that $Cu_{10}Zr_7$ nanocrystals can be formed after ultrasonic vibrations. The evolution of nanocrystalline particles leads to an increase in plasticity during compression at room temperature in combination with an increase in the yield strength.

Currently, the construction of gradient structures has become a successful strategy in the development of advanced metallic materials with excellent performance properties. By ultrasonic vibration treatment, it was possible to form a gradient amorphous-nanocrystalline structure in $Zr_{46}Cu_{46}Al_8$ bulk amorphous alloy [67]. Using 20 kHz ultrasonic cyclic loading in the elastic mode, it is possible to obtain gradient structures with different volume fractions of crystallised substance in less than 2 s by adjusting the input ultrasonic energy. This innovative approach has clear advantages: it is extremely fast, requires minimal stress, and allows adjusting easily the degree of structural gradients by fine adjustment of the processing parameters. Nanoindentation tests show higher hardness near the impact surface, which is explained by a higher degree of nanocrystal formation, which gradually decreases with depth. As a result of the gradient dispersion of nanocrystals after ultrasonic treatment, increased plasticity of $Zr_{46}Cu_{46}Al_8$ AA was found, characterised by the formation of multiple shear bands. Microstructural studies show that nanocrystallization induced by ultrasonic treatment occurs due to local atomic rearrangements in phase-separated regions rich in Cu with high diffusion mobility.

The study of the effect of ultrasonic mechanical activation on the structural-phase transformations of $Ti_{50}Ni_{25}Cu_{25}$ AA carried out by the authors of [34] using differential scanning calorimetry (DSC) showed that this method of action affects the crystallization parameters and martensitic transitions. Temperatures and energies of crystallization increase after processing of amorphous ribbons in a longitudinal vibration waveguide. In turn, after processing of AA ribbons in an ultrasonic anvil, crystallization temperatures increase, and the crystallization energy decreases. The study of martensitic transformations showed that processing in an ultrasonic anvil leads to a decrease in characteristic temperatures and the magnitude of thermal effects, which may indicate a decrease in the grain size of the crystalline phase.

Using ultrasonic vibrations, a method for producing a series of composites from La-based amorphous alloys is proposed [68]. By modulating the amplitude and time of ultrasonic action, controlling the input energy of high-frequency vibrations, such composites with different proportions of the crystalline phase can be produced easily and accurately in seconds at low pressure and room temperature. By varying the degree of crystallinity, reduced hardness and better plasticity of AA composites are achieved compared to samples in the cast state.

Combining two technologies (ultrasonic treatment with multiple rolling) as applied to $Fe_{78}Si_{13}B_9$ and $Al_{87}Ni_8Gd_5$ AAs promotes an increase in the amount of free volume in the amorphous phase and leads to a significant acceleration of the AA crystallization processes [69; 70].

In [39], changes in the surface morphology and structure of the $Fe_{73.6}Si_{15.8}B_{7.2}Cu_{1.0}Nb_{2.4}$ ribbon AA (Finemet) as a result of severe deformation using ultrasonic impact treatment at room temperature in air were studied. The AA surface morphology after ultrasonic impact treatment is the result of localised plastic deformation occurring through the formation of a large number of shear bands. The effect of structural-phase transformation in the volume of the Finemet ribbon during ultrasonic impact treatment is caused by an increase in atomic mobility during deformation, which can be sufficient for the formation of nanocrystals by the diffusion mechanism and their uniform distribution in the amorphous matrix.

4. Ultrasonic material joining technologies

4.1. Alternative consolidation methods

One of the reasons limiting the large-scale application of ribbon and bulk amorphous alloys is their geometric dimensions. The thickness of commercial rapidly melt-quenched AA ribbons typically ranges from 20 to 30 μm, and the width – from 1 to 100 mm. The diameter/thickness of massive amorphous metal rods or plates can vary from 1 to 50 mm, and their length is usually no more than 80 mm. Moreover, AA often needs to be joined with other crystalline alloys in technical applications. Therefore, the development of AA/AA, AA/metal, AA/crystalline alloy joining methods has attracted much attention from researchers. Amorphous alloy can become brittle due to crystallization upon heating [1; 7]. Considering this fact, joining temperatures should be maintained below the glass transition temperature of amorphous alloy. Attempts have been made to use various methods for AA/AA and AA/crystal joining. In particular, spark welding was used to join $Zr_{55}Al_{10}Ni_5Cu_{30}$ AA and crystallization in the joint was successfully avoided [71]. The results showed that the tensile strength of the produced joints was equal to the strength of the original AA. In similar experiments, electron beam welding was used to consolidate the $Zr_{41}Be_{23}Ti_{14}Cu_{12}Ni_{10}$ AA plate with metallic nickel [72]. In [73], friction welding was tested to join $Pd_{40}Ni_{40}P_{20}$ / $Pd_{40}Cu_{30}P_{20}Ni_{10}$, $Zr_{55}Cu_{30}Al_{10}Ni_5$ / $Zr_{41}Be_{23}Ti_{14}Cu_{12}Ni_{10}$ together. It was shown that amorphous alloys could be joined at temperatures approximately 50 K below the glass transition temperature without demonstrating crystallization at the interface.

4.2. Ultrasonic soldering

Ultrasonic soldering is a flux-free method that can operate in air. Ultrasonic vibrations help to improve the initial wetting conditions at the solder/substrate interface [74; 75]. In this context, ultrasonic soldering can be used to join some materials that are difficult to wet. Moreover, this type of soldering can realise a connection through the low-temperature eutectic solder/substrate phase [75; 76]. Thus, ultrasonic soldering serves as an effective method for joining amorphous alloys at temperatures significantly below their crystallization temperatures.

Melt-quenched iron-based amorphous foils are among the superior soft magnetic materials used in amorphous motors. Producing a strong connection between them is a complex technical task when assembling amorphous stators with aluminium shells. The use of ultrasound with a resonant frequency of 27 kHz and a vibration amplitude of 15 μm in the soldering process, it was possible to join qualitatively the $Fe_{77}Si_{14}B_9$ amorphous alloy with an aluminium sheet at temperatures of 250–350 °C for 10 s [77]. Sn–Zn filler was used as a welding filler material. A $FeZn_{13}$ compound was found at the filler metal/amorphous alloy interface. The results showed that the initial wetting of the interface and the refinement of the microstructure were improved under the action of ultrasonic vibrations.

The characteristics of wetting the $Zr_{55}Al_{10}Cu_{30}Ni_5$ amorphous alloy using Sn–Cu–Ni solder were studied using 40 kHz ultrasonic vibrations in open air at 528 K for 90 s [78]. It was found that wetting mainly depends on the collapse of cavitation bubbles on the AA surface, initiating erosion. Such cavitation erosion is effective for immediate removal of the passivation film from the AA surface. The sono-capillary effect, which is also caused by ultrasonic vibration, improves the adhesive properties of the solder.

In [79], the behaviour of wetting pure tin with respect to the $Zr_{50.7}Cu_{28}Ni_9Al_{12.3}$ amorphous alloy was studied under ultrasonic treatment (20 kHz) and a pressure of 0.2 MPa. Heating to 300 °C without ultrasound showed a non-wetting state of Sn for the amorphous alloy. Ultrasonic vibration promoted the wetting of Sn. Before ultrasonic treatment for 30 s, only physical adsorption was observed at the Sn/AA interface. Increasing the ultrasonic treatment time led to a change in the bonding at the Sn/AA interface from a point contact to a local surface contact and a diffusion layer. Two bonding modes were found at the Sn/AA interface. In the order-order bonding mode, slight crystallization occurred inside the amorphous alloy near the interface. The filler metal was bonded to the amorphous alloy through an ordered structure. In the order-disorder bonding mode, the filler metal and the amorphous alloy retained their original structures. The interface was characterised by stepped layers. The Cu content was higher than that of other elements near the bonding boundary. Longer diffusion distances of Sn in the amorphous alloy were obtained at high ultrasound power, high temperature (up to 400 °C), and large immersion depth (up to 3 mm).

4.3. Ultrasonic powder consolidation

The work [80] reports the successful production of two-phase composites of $Zr_{55}Cu_{30}Ni_5Al_{10}$ and Al-6061 aluminium alloy using ultrasonic powder consolidation at low temperatures and stresses. A wide range of composites with individual compressive strength and plasticity were obtained by optimizing the mass ratios of $Zr_{55}Cu_{30}Ni_5Al_{10}$ and Al-6061 powders. Mechanical tests showed that increasing the aluminium content improved plasticity while maintaining significant strength. In particular, the composite with a mass ratio of 5:5 demonstrated the best balance of mechanical properties, excellent compaction, homogeneity without visible defects, and a relative density in the range from 92 to 99 %. Microstructural analysis revealed the formation of a tightly bonded interface with the diffusion layer. This confirms that high-quality bonding was facilitated by ultrasonic vibration. Moreover, the ultrasonic powder consolidation process has successfully produced complex shapes from materials (star-shaped, toothed). This innovative approach is promising in the development of high-quality lightweight composites to meet the requirements of advanced manufacturing applications.

4.4. Ultrasonic welding

There are reports of successful production of "sandwich" composites from $Zr_{35}Ti_{30}Cu_{8.25}Be_{26.75}$ ribbon amorphous alloy and $Al_{80}Li_5Mg_5Zn_5Cu_5$ high-entropy alloy (HEA) [81], as well as from $La_{55}Al_{25}Ni_5Cu_{10}Co_5$ amorphous alloy and $Co_{20}Cr_{20}Fe_{20}Ni_{20}Mn_{20}$ HEA [82] using ultrasonic excitation. The ribbons were first folded together using a clamping force and then subjected to high-frequency (20 kHz) vibrations of an ultrasonic sonotrode that lasted for several seconds. During this process, the amorphous alloys softened and bonded into a bulk mass with the HEA ribbons. This low-temperature low-stress method allowed creating composites that combine the properties of both amorphous and crystalline components. Microscopic studies and computed tomography show good bonding quality without pores and cracks in the composites of AA and HEA. Due to the unique structure combining soft and solid phases, the composite has improved mechanical properties compared to those obtained from a pure single phase.

In the process of ultrasonic welding when joining AAs to each other or to other materials, crystallization of the amorphous structure can be prevented due to the weak thermal effect and the quickness of the process. Other advantages of this technology include energy efficiency and the absence of the need for welding consumables. An important feature is also the ability to join materials with different melting temperatures, since the process occurs in the solid state.

Ultrasonic welding was used to join a sheet of commercial forged aluminium alloy (AA5754) 1 mm thick and a strips of $Zr_{59.3}Cu_{28.8}Al_{10.4}Nb_{1.5}$ commercial bulk amorphous alloy (AMZ4) 0.4 mm thick [35]. The following process parameters were proposed: welding energy was 2000 W·s, displacement amplitude was 41 μm, and welding force was 740 N. The results showed that the AA retains its amorphous structure in the joint, and the joint strength is higher than the strength of the Al sheet. In [83], a technology was considered in which, using a normal pressure of 80 N, a vibration time of 1 s, and a frequency of 20 kHz, three-dimensional plates of $Cu_{54}Zr_{22}Ti_{18}Ni_6$ AA with a thickness of 1 mm were successfully "welded" without any signs of crystallization. In [32], it was similarly shown that ultrasonic welding could be used to consolidate $Zr_{55}Cu_{30}Ni_5Al_{10}$ amorphous alloys with each other, maintaining the bonding zone in an amorphous state. The joint area can be increased by using the gluing condition with external heating to a temperature of 423 K (below the glass transition temperature).

Using ultrasonic welding, joints of bulk $Zr_{62}Cu_{33}Al_4Ti$ AAs with hypoeutectic Zn–3Al filler metal were produced [84]. A thick wavy layer consisting of alternating $Zn_{50}Al_{25}Zr_{25}/Zn_{22}Zr$ sublayers was formed on the surface of the Zr-based AA substrate, which provided a shear strength of about 100 MPa for the welded samples.

It should be separately noted that a method for producing multilayer AA ribbons using ultrasonic welding has been developed. This method can be used as an ultrasonic additive manufacturing process, such as 3D printing, in which thin metal strips are laid layer by layer to obtain thicker metal samples. It can be imagined that if the AA ribbons can be infinitely superimposed on each other under the action of ultrasonic vibrations, then the glass-forming capacity limitation on the AA dimensions will no longer exist. Fig. 3 schematically shows the principle of consolidating samples using ultrasonic welding.

Using ultrasonic welding technology, 4–5 pieces of Fe–Si–B AA ribbons with a joint area of up to 8×8 mm^2 (each layer thickness was 25 μm) were successfully and quickly (in 220 ms) joined [85]. The operating frequency, ultrasound amplitude, and maximum output power of the ultrasonic welding equipment were 20 kHz, 35 μm, and 4000 W, respectively. Similarly, multilayer $Ni_{82.2}Cr_7B_3Si_{4.8}Fe_3$ AA ribbons were joined using ultrasonic welding, which were laid in 3–4 layers (each layer thickness was 40 μm) [86]. Moreover, ultrasonic welding was used to prepare composite samples in which two crystalline Al and Cu ribbons were joined with $Ni_{82.2}Cr_7B_3Si_{4.8}Fe_3$ AA ribbons [87]. However, the laminated AA and metal-AA composites produced in the above-mentioned works can be welded only in several layers, and the alternate, unlimited stacking, as in 3D printing, has not yet been achieved [88].

It should be noted that, taking into account the morphology of the joints and the phase stability, ultrasonic welding treatment demonstrates powerful capabilities for consolidating amorphous alloys both in air and in liquid media. In [89], bulk $La_{55}Al_{25}Ni_5Cu_{10}Co_5$, $Zr_{55}Cu_{30}Al_{10}Ni_5$ amorphous alloys and high-entropy Ti–Zr–Hf–Be–Ni amorphous alloy were selected for ultrasonic joining in fresh and sea water, in alcohol, and in liquid nitrogen. It was shown that the technology using ultrasonic vibration eliminates high temperature and problems associated with high current (as in the case of conventional underwater joining methods). Moreover, the samples from the studied amorphous alloys both had no obvious defects in the joined interface and demonstrated excellent mechanical properties and corrosion resistance. This approach both provides an effective underwater joining method for on-the-shelf and marine applications and ensures a feasible joining strategy in extreme conditions such as flammable environments in oil, gas, organic solvents and cryogenic conditions in space.

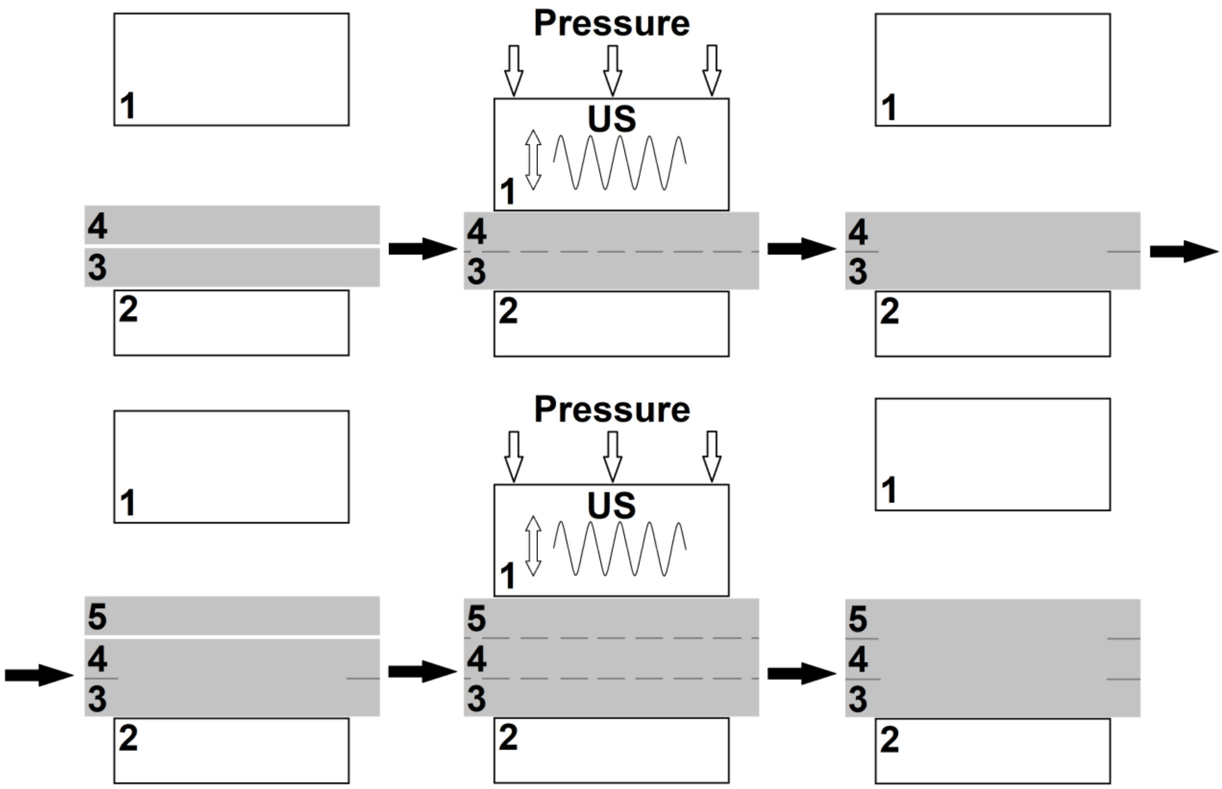

Fig. 3. *Schematic diagram of ultrasonic vibration welding:*
1 – sonotrode; 2 – fixture; 3, 4, 5 – layers of amorphous alloys
Рис. 3. *Схема УЗ вибрационной сварки:*
1 – сонотрод; 2 – установочная плита; 3, 4, 5 – слои аморфных сплавов

DISCUSSION

In most publications on ultrasonic processing, the object of study is massive amorphous alloys produced in the form of rods, bars, plates. Increased interest clearly implies expanding the boundaries of their use both as a functional and as a construction material. Currently, bulk AAs are integrated into jewellery, sports equipment (for example, golf clubs and tennis rackets), used for the production of biocompatible implants, mobile phone cases, and applied for reinforcement [3; 5; 6]. Ultrasonic forming has broad prospects for overcoming the size limitations of cast amorphous alloys, synthesizing new composites based on them. Nano-, micro- and miniature products of complex shapes currently produced in laboratory conditions using ultrasonic stimulation of bulk AAs will later be able to compete with similar products made of traditional metals and alloys. Moreover, the US and Japan are developing defence industry products, in particular, for the creation of lightweight and durable composite armour plates based on ceramics and bulk AAs, as well as for the replacement of the core material in anti-tank armour-piercing shells with composites made of AAs due to their similar density and performance properties [90].

However, in Russia, bulk amorphous alloys have not yet found their large-scale application due to their difficult machinability; they are cast exclusively for research purposes for fundamental science. Therefore, it is reasonable to adopt the accumulated world experience in the use of ultrasonic technology. Being an effective and convenient method of subsequent processing to improve the final plasticity of bulk AAs, ultrasonic modification will be of great importance for their further development and commercialization in Russia.

In turn, amorphous, amorphous-nanocrystalline ribbons and microwires are manufactured on an industrial scale in Russia. PJSC Ashinsky Metallurgical Plant (Asha), PJSC M-STATOR (Borovichi), and R&D Company GAMMAMET (Yekaterinburg) are the largest and most well-known manufacturers in the market. Their rapidly melt-quenchered ribbons are best known primarily for a high level of magnetic and corrosion properties and are used in electrical products, transformers, magnetic screens, and as components for protective coatings. In this regard, it is extremely important to continue studying the effect of ultrasound on amorphous alloys with an emphasis on the behaviour of their magnetic and chemical properties. Judging by the literature, it is here that an obvious gap is noticeable. Most of the studies conducted were focused on improving the mechanical response of AAs after ultrasonic vibrations, and the study of corrosion resistance, magnetic behaviour, and catalytic activity was not given due attention. Meanwhile, the use of ultrasonic energy can provide saturation magnetization significantly higher than that achieved with conventional annealing, along with a low coercive force. For manufactured iron-based amorphous alloys, the use of ultrasonic vibrations can promote the balanced formation of uniformly distributed ferromagnetic nanoclusters, which will reduce anisotropy and, thus, increase the soft magnetic properties of the ribbons. Moreover, the effect of ultrasonic vibrations is quite capable of improving the corrosion resistance of AAs in aggressive environments. It should be understood that the corrosion resistance of amorphous alloys both depends on the alloying elements and is closely related to their metastable amorphous structure. As practice has shown, ultrasonic treatment of AAs can produce an amorphous-nanocrystalline state [64; 65; 67], which is characterised by a decrease in the average atomic distance. A more stable structure will lead to some decrease in the chemical potential and will contribute to an increase in corrosion resistance. Thus, it is advisable to initiate scientific studies of the susceptibility of amorphous alloys to chemical action after ultrasonic modification.

Selective ultrasonic stimulation has great potential for adaptation of local nano-, microstructure and properties of amorphous alloys: it is possible to achieve simultaneously rejuvenation in areas of close packing of atoms with a decrease in the elastic modulus and relaxation in areas of loose packing, suppressing the nucleation of the first shear bands. In addition, the size, length and pattern of rejuvenated zones can be adjusted as needed.

Introduction of free volume and a small amount of dispersed nanocrystals into amorphous alloys due to ultrasound treatment allows improving their complex characteristics (increasing plasticity and strength). However, it is important to learn how to obtain controllably the optimal ratio of amorphous and crystalline components, adjusting the efficiency of ultrasound transmission and avoiding the transition from plasticity to brittleness, by controlling the ultrasound amplitude and preliminary loads. The nature of embrittlement and attenuation of ultrasonic waves in such a structural state is not completely clear.

To date, published data on ultrasonic excitation modes as applied to amorphous alloys are not complete, few in number and scattered. It is necessary to accumulate and expand this experimental knowledge for various chemical compositions of both bulk and, to a greater extent, AAs ribbons. Nevertheless, we have attempted to collect the information of interest on the main parameters, distributing it in accordance with the ultimate goal of ultrasonic processing, which the researchers set in their experiments: rejuvenation and forming of amorphous alloys, nanocrystallization from an amorphous state or joining the material by ultrasonic welding/soldering (Table 1). Analysing the obtained data, we can conclude the following.

1. Bulk amorphous alloys are studied more intensively than ribbon ones, and it is expected that there is more information on the main parameters of their ultrasonic excitation.

2. There are two generalised methods of ultrasonic modification of amorphous alloys: a noncontact method, when high-frequency vibrations are transmitted through a liquid medium in an ultrasonic bath, and a contact method, i.e. using an ultrasonic sonotrode directly adjacent to the AA. In most cases, researchers use the second method, since it has proven itself to be faster and more effective in its influence on the AA structure.

3. To implement softening and structural renewal of amorphous alloys, the frequency of ultrasonic treatment f is 20 kHz, the time of exposure t is very short – from 80 to 950 ms, the amplitude A varies from 19 to 44.4 μm.

Table 1. *Modes of ultrasonic treatment for ribbon and bulk amorphous alloys*
Таблица 1. *Режимы УЗ обработки для ленточных и объемных аморфных сплавов*

Chemical composition of amorphous alloys, at. %	Ultrasonic treatment parameters					Source
	***f*, kHz**	***A*, μm**	***t*, s**	***E*, J**	***W*, W**	
Structural rejuvenation and forming						
$La_{60}Ni_{15}Al_{25}$	20	40	–	–	–	[45]
$La_{55}Al_{25}Ni_{5}Cu_{10}Co_{5}$ $Al_{86}Ni_{9}La_{5}$ $La_{60}Al_{20}Ni_{20}$ $Cu_{50}Zr_{50}$ $Pd_{40}Cu_{30}P_{20}Ni_{10}$ $Zr_{35}Ti_{30}Cu_{8.25}Be_{26.75}$ $Fe_{78}Si_{9}B_{13}$ ribbons	20	40–44.4	1	–	–	[51] [52] [48]
$La_{55}Al_{25}Ni_{5}Cu_{10}Co_{5}$	20	–	0.08–0.24	5–30	–	[91]
$Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_{5}$	20	19–36	–	–	–	[44]
$Zr_{46}Cu_{46}Al_{8}$	20	40	0.6–0.95	50–400	83–205	[67]
Partial nanocrystallization						
$Cu_{52.71}Ti_{28.06}Zr_{11.59}Ni_{7.54}$ – ZnB amorphous composite	20	15–50	–	–	–	[64]
$Zr_{44}Ti_{11}Cu_{10}Ni_{10}Be_{25}$	20	24	–	–	–	[33]
$Zr_{46.75}Cu_{46.75}Al_{6.5}$	20	15	7200	–	–	[66]
$Ti_{50}Ni_{25}Cu_{25}$ ribbons	22	10	720–1800	–	–	[34]
$La_{64}Al_{14}Cu_{22}$	20	4–14	–	100–700	–	[68]
$Fe_{78}Si_{13}B_{9}$ ribbons $Al_{87}Ni_{8}Gd_{5}$ ribbons	37	–	720–1800	–	100	[69] [70]
$Fe_{73.6}Si_{15.8}B_{7.2}Cu_{1.0}Nb_{2.4}$ ribbons	21	25	10–60	–	600	[39]
Joining via ultrasonic welding/soldering						
$La_{55}Al_{25}Ni_{5}Cu_{10}Co_{5}$ / $Zr_{55}Cu_{30}Al_{10}Ni_{5}$ / TiZrHfBeNi	20	44.4	–	300–700	2500	[89]
AA5754 aluminum alloy / $Zr_{59.3}Cu_{28.8}Al_{10.4}Nb_{1.5}$	20	41	–	2000	–	[82]
Al / $Fe_{77}Si_{14}B_{9}$ ribbons	27	15	10	–	–	[77]
Sn–Cu–Ni / $Zr_{55}Al_{10}Cu_{30}Ni_{5}$	40	5.1–7.4	90	–	–	[78]
Sn / $Zr_{50.7}Cu_{28}Ni_{9}Al_{12.3}$	20	–	5–3600	–	–	[79]
$Fe_{78}Si_{9}B_{13}$ ribbons to each other	20	35	0.22	–	4000	[85]
Al / Cu / $Ni_{82.2}Cr_{7}B_{3}Si_{4.8}Fe_{3}$ ribbons	35	–	–	–	800	[86]

Note. A is the amplitude of ultrasonic vibrations;
f is the frequency of ultrasonic vibrations;
t is the ultrasonic exposure time;
W is the power;
E is the energy of ultrasonic equipment.
Примечание. A – амплитуда УЗ колебаний;
f – частота УЗ колебаний;
t – время УЗ воздействия;
W – мощность УЗ установки;
E – ее энергия.

At lower amplitudes, AAs usually pass into a state with lower potential energy, similar to the aging effect.

4. To transfer amorphous alloy into a partially nanocrystalline state, a longer ultrasonic treatment is required than for rejuvenation (from 10 s to 2 h). In this case, the frequency range is expanded (f=20–37 kHz) along with the amplitude range (A=4–50 µm).

5. During ultrasonic welding/soldering of amorphous alloys, the following ranges of ultrasonic characteristics can be noted: f=20–40 kHz, A=5.1–44.4 µm. As for the time of ultrasonic action, for joining micron AAs ribbons with each other or with another material, it is necessary from 220 ms to 10 s, and for bulk AAs with a thickness of several centimetres, it will take up to 1 h.

6. The highest values of energy E and power W of ultrasonic devices are noted during ultrasonic welding (E=300–2000 J, W=800–4000 W), average values – during partial nanocrystallization (E=100–700 J, W=100–600 W), and the lowest – during structural rejuvenation and forming of AAs (E=5–400 J, W=83–205 W).

An interesting and attractive idea is to build extreme effects, including ultrasonic modification, into one integral technological chain [1]. This can lead to qualitative changes in the nature of the final structure and, consequently, to the possibility of obtaining unique properties of metallic materials subjected to complex effects. With regard to amorphous alloys, individual links of the chain are already successfully implemented: for example, melt quenching (MQ), during which AAs are created, and their subsequent severe plastic deformation (SPD) in a Bridgman chamber, or MQ + laser irradiation (LI), or MQ + ultrasonic treatment (UST), or MQ + cryogenic deformation (CD). For the successful implementation of systemic multi-stage treatment, for example MQ → SPD → CD → LI → UST, it is necessary to "synchronise" the parameters for the material to obtain new structures and structure-sensitive properties. This research layout is innovative, but has not yet been sufficiently reflected in the scientific literature.

CONCLUSIONS

Processing of amorphous alloys into desired shapes and structures is a prerequisite and basis for their successful commercial application. A promising method of influencing AAs (non-destructive, environmentally friendly and inexpensive) both from a fundamental and from practical point of view is the use of high-frequency ultrasonic vibrations. However, to date, many aspects concerning the physical nature of structure formation in amorphous alloys, the mechanisms of their plastic deformation, crystallization, and the response of physicochemical properties during ultrasonic processing remain unclear.

It is important to continue identifying in detail the relationships between the sequence of structural-phase transformations in amorphous alloys and the parameters of ultrasonic processing. This will expand the existing scientific knowledge in the physics of disordered and nonequilibrium systems, and will allow for a comprehensive formulation of conditions and accurate determination of modes that promote:

– the structure rejuvenation with softening and improvement of thermal stability while maintaining amorphousness;

– partial devitrification of AAs with an optimal combination of the proportion of amorphous and nanocrystalline phases, a compromise balance of strength and plasticity, as well as the preservation of soft magnetic properties;

– cold welding of layers of amorphous alloys different in compositions and properties with high-quality adhesion, i. e. the creation of hybrid materials.

Understanding the scientific principles of these processes using ultrasound is extremely important for the effective management of properties of amorphous alloys and the creation of innovative multifunctional materials based on them.

Studying the influence of ultrasonic treatment on the thermal stability of AAs will allow expanding the temperature ranges of their operation without embrittlement.

Shear punching of amorphous alloys under the influence of high-frequency vibrations is an innovative method of their forming. The method is not limited to the punch profile, and it is possible to manufacture more target products with different shapes. Such advantages as low cost, fast operation speed and good product quality make the process of forming AAs an energy-saving and effective technology with wide application prospects.

The study of the influence of ultrasonic mechanical activation on the structure will help to understand the mechanisms of structural rearrangements, activation of defects in amorphous alloys under the action of ultrasonic vibrations. This, in particular, helps to identify the physical causes of superplastic flow in a glassy system using cold ultrasonic treatment. Ultrasonic forming using the phenomenon of superplasticity of amorphous alloys in a supercooled liquid state can become an advanced method for manufacturing circuits, relief images, parts from AAs with sizes from nanometres to centimetres. This opens up inviting prospects in engineering applications, for example, in microelectronics and nanotechnology, for the creation of components, integrated circuits, chips, printed circuit boards.

The results of cold welding of dissimilar amorphous alloys stimulate further development of high-tech manual design and manufacture of intelligent materials containing several phases and compositions. Ultrasonic forming of AAs will provide a new method for manufacturing structures and large-sized AAs with great potential for future developments. Ultrasonic processing can be used when creating high-speed devices, planar mechanisms, for example, to create actuators in microelectromechanical systems based on crystallization using ultrasonic vibrations of TiNi amorphous thin films with shape memory. The advantage of this method is that the shape memory properties can be spatially distributed taking into account the specified requirements.

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Влияние ультразвуковой обработки на структурные превращения и механическое поведение аморфных сплавов (ОБЗОР)

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Аннотация: Широкое применение аморфных сплавов осложнено узким диапазоном их термической стабильности, охрупчиванием при повышенных температурах, труднообрабатываемостью, низкой пластичностью при растяжении. Ультразвуковая обработка является инновационным методом для решения этих проблем. Встраивание в технологическую цепочку ультразвуковой технологии может способствовать совершенствованию эксплуатационных характеристик аморфных сплавов, изготовлению из них деталей на разных масштабных уровнях, а также качественному соединению с другими материалами. Влияние ультразвуковых вибраций на структурные превращения и механическое поведение аморфных сплавов изучено не в полной мере. Отсутствие целостного научного обоснования физических процессов и сопутствующих эффектов в аморфных сплавах при ультразвуковом возбуждении препятствует развитию соответствующей технологии и оптимизации ее режимов. За последнее десятилетие исследователи предложили различные методики ультразвуковой обработки аморфных сплавов для улучшения их формуемости, достижения баланса пластичности и прочности, консолидирования друг с другом и с металлами. Кроме того, развиты определенные представления об омоложении их структуры, о возможностях перевода в частично нанокристаллическое состояние под действием ультразвука. Чтобы подвести итог этим разработкам, приводится систематическое обсуждение особенностей, параметров и режимов ультразвуковой обработки применительно к ленточным и объемным аморфным сплавам для улучшения их структурочувствительных свойств. На этой основе рассматриваются ограничения текущих исследований. К наиболее перспективным применениям ультразвуковых технологий для быстрозакаленных сплавов в ближайшем будущем следует отнести: их аддитивное производство, создание гибридных композитов за счет ультразвуковой сварки, ультразвуковое формование для изготовления изделий сложных форм и геометрии, комплексную многоэтапную обработку для получения уникального сочетания свойств (например, закалка из расплава → лазерное облучение → ультразвуковое стимулирование). Настоящий обзор расширяет существующие знания об ультразвуковом управлении свойствами, структурой аморфных сплавов и облегчает исследователям быстрый поиск ссылок по данной тематике.

Ключевые слова: аморфный сплав; ультразвуковая обработка; структурные превращения; механическое поведение; нанокристалл; омоложение структуры; композит; пластичность; формование.

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