Processes, occurring in metallic ribbon glasses, under the synergistic impact of the mechanical loading and impulse electrical current

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Abstract. It has been experimentally established, that reversible electro-plastic effect, which is similar to the well-known case in crystalline metals, is observed on the \( \sigma(\varepsilon) \) diagrams for ribbon metallic glasses (MG). It has been established that passing of the impulse electrical current through the loaded specimen of MG leads to the larger fall of the mechanical stress than furnace heating at the same temperature. A linear relation between the fall of mechanical stress and temperature, depending on alloy composition, is observed. Growth of the duration of a current impulse at constant current density increases heating of the specimens with the larger reversible fall of the mechanical stress. Value of the reversible fall of mechanical stress, obtained with the impulses of electrical current in amorphous alloy, is caused not only by thermal expansion but also other reversible processes that are the result of the impact on amorphous alloys (for example, structural relaxation, that is reversible on the initial stage).

1. Introduction

The electro-plastic effect is a phenomenon of loss in mechanical stress of deformation of a metal at the passing of the impulse electrical current through it [1]. This effect is efficiently used at the treatment of the traditional materials (steels, copper, aluminium alloys etc.) [2] and durable metals (tungsten, molybdenum) [3]. The technologies of electro-plastic treatment of metals let to have a new quality of the products, fabricated with them; particularly, they decrease the number of the defects in the crystalline structure of a material [4]. Nowadays, there are known many scientific works on electro-plastic effect in different metals and alloys [5].

The electro-plastic effect in metallic materials is observed under the impulse electrical current ~ \( 10^9 \) A/m². A result of the current impact on plastic deformation in metals with that density is sufficient growth of plasticity (to tens of per cent in opposition to equivalent heating) and reduction of wear-resistance of the investigated specimens [6].

In the work [7], a try of detection of electro-plastic effect in amorphous and nanocrystalline alloys has been done. The author decides the absence of the electro-plastic effect in these materials. Herewith, in the work [8], it has been shown that the reversible fall of a mechanical load, wherein irreversibility occurs as a deviation from the linear view of the \( \sigma(\varepsilon) \) diagram with residual deformation, takes place at unloading and growth of mechanical loading with impulse current through the amorphous and nanocrystalline specimens.
Metallic alloys (MG) [7-9] and the products from them are widely used, undergone to the different impacts: mechanical, electromagnetic, thermal, radioactive etc. and also all together, during exploitation [10-14]. Investigations of MG are carried out from the second half of the previous century, but there is no uniform structural model for the properties of these materials yet. The results of the investigations of MG [15-21], underwent to the different impacts, are ambiguous. While the uniaxial extension of MG, at the room temperature, small relative elongation $\delta \approx 0.02-0.3\%$ is observed. That is the small value, but MG can be considered as ductile in opposite to traditional glasses ($\delta \approx 0$). That is also in evidence from that MG yield to rolling and, consequently, they are plastically deformed. Elastic deformation of MG reaches the value of 2% [12].

Investigation of the behavior of strongly non-equilibrium structures (for example, amorphous metallic glasses) in the case of electromagnetic impact is one of the significant tasks in physics of condensed matter.

The goal for this work – determination of the processes, occurring in loaded MG that are responsible for the fall of the mechanical stress during the synergistic impact of the impulses of electrical current.

2. Materials & Experimental Methods
Cobalt-based MGs with different base contents [22], obtained by the spinning method, were taken as research materials. Samples with dimensions of 90×3.54×0.02 mm were used. Uniaxial stretch of the specimens we performed with Instron-5565 an electromechanical static machine with loading rate 0.1 mm/min. A scheme of the experiment has been depicted in figure 1. For the current passing, we performed charging of the capacitor up to the fixed value that controlled with the parallel coupling voltmeter and the voltage-dropping resistor. Passage of the impulse electrical current (by discharging of the capacitor) we carried during the deformation of a specimen. As resistivity of the connecting wires is insignificant ($R \sim 10^{-4}$ Ohm) in compare with the resistance of the MG specimens, their contribution in the electrical impulse was not considered.

![Figure 1. A scheme of the experimental equipment: 1 – computer, 2 – Testo-845, 3 – Instron 5565, 4 – sample.](image)

Current density, passing through the specimen, was varied from $1\times10^8$ to $5\times10^9$ A/m² with the impulse duration $\tau \sim 2.5$ and 5 ms. By a Testo-845 laser pyrometer, we measured heating of the specimens during the whole deformation process with the frequency $10^{-1}$ s. The most important part is the consideration of the Joule effect that consists of the precise measurement or calculation of the heating in the specimens with the estimation of its impact on the deformation. For that goal, we carried out the extension tests on the specimens in the temperature interval from 296 to 366 K without passing of the impulses of electrical current. We carried out the investigations by the following scheme. At the attainment of the arbitrary stress $\sim 600$ MPa, the deformation was stopped, but
herewith loading was not removed from the specimen. After that, the heating of the loaded specimen was realized in the furnace from the Instron-5565 machine until the temperature difference reached to the fixed value $\approx 10$ K, $\approx 20$ K, $\approx 30$ K, $\approx 40$ K, $\approx 60$ K relatively to the room temperature. Further deformation of the specimens was carried out with the same rate that was on the first stage, but it was already chosen higher temperature of the specimen. Herewith we determined the value of a mechanical fall, caused by the heating.

3. Results & Discussion

For all investigated alloys, the $\sigma(\varepsilon)$ diagrams have been received at the synchronic passage of the impulse current with a different value. Simultaneously, we registered the corresponding temperature relations of heating of the specimens. A typical view of the dependencies is shown in figure 2. As it is seen from figure 2, the passing of the current impulse is accompanied by the momentary fall ($\sim 1$ s) of the mechanical stress and the temperature leap.

![Figure 2](image)

**Figure 2.** The loading diagram of the AMAG-180 alloy: a) at exposing of 13 current pulses with a duration of $\tau \approx 2.5$ ms; b) the corresponding temperature–time dependence.

By the results of the stretching experiments, it was established that the general trend of the $\sigma(\varepsilon)$ diagrams does not practically change under variation of the loading rate. The Young’s moduli of the materials and their tensile strength, whose values do not practically depend on deformation rates, have been determined (table 1).

| Alloy           | $\sigma$, MPa | $E$, GPa |
|-----------------|---------------|----------|
| AMAG-170        | 1548±3        | 97,9±4,5 |
| AMAG-172        | 1307±44       | 103,3±9,1|
| AMAG-179        | 1268±283      | 112±0,4  |
| AMAG-180        | 2032±481      | 141,3±28,9|
| AMAG-183        | 1529±22       | 105,1±7,3|
| AMAG-186        | 1696±145      | 117,9±5,5|

Table 1. Tensile strength and Young’s modulus for ribbon metallic glasses.

Influence of the duration of an electrical impulse on the trend of the mechanical fall has been investigated. It has been established that for the same current density, more duration of impulse leads to bigger fall of mechanical stress. Comparative graphs of mechanical decreases are similar qualitatively for all investigated alloys. The characteristic dependence has been shown in figure 3.

While passage of the impulse electrical current, the sharp temperature jump of a specimen occurred inevitably because of Joule heat. The dependencies of the mechanical fall from temperature changing in specimens have been plotted in figure 4. The obtained graphs were approximated with the linear
functions. Thus, growth of the mechanical fall is in direct proportion to temperature changing in specimen.

![Figure 3](image1.png) ![Figure 4](image2.png)

**Figure 3.** Dependence of the mechanical stress relief of AMAG-180 alloy from the current density, acting on the sample. **Figure 4.** Depending on the magnitude of the mechanical stress, relief of some alloys changes on temperature under pulse current.

Furnace heating of all investigated alloys has shown that relation between the stress difference $\Delta \sigma$ and temperature difference $\Delta T$, caused by heating, also has a linear form (figure 5), which is similar to the experiments with the passing of the impulse electrical current (figure 4).

By the results of the experiments, it has been established that passing of the impulse current leads to a larger fall of mechanical stress for all alloys in opposed to furnace heating. Comparative relations of the stress difference have been shown in figure 6.

![Figure 5](image3.png) ![Figure 6](image4.png)

**Figure 5.** Relationship between stress difference and temperature difference, caused by the furnace heating **Figure 6.** Comparative graphs of reducing the mechanical stress in AMAG-180 alloy at heating temperature: when passing current pulses (1) and when heated in a furnace (2).

Using of Hooke’s law and equation for thermal expansion permitted to estimate addition of the furnace heating in fall of mechanical stress at deformation. It has been shown that it consists of 55-65% of the whole decrease in stress. Obviously, another part of the decrease is contributed by the structural relaxation, occurring at the heating. From the $\sigma(\varepsilon)$ diagrams, the $\Delta \sigma$ and $\Delta T$ values, received
during the passing of the impulse electrical current through all alloys, have been established. Also by using the equation for thermal expansion and Hooke’s law for elongation, we obtain some values in a view: \( \Delta l_y = (\Delta \sigma \times l_0)/E \). Calculated values pertain to the interval \( 12.7 \times 10^{-5} \text{ m} - 55.15 \times 10^{-5} \text{ m} \) depending on composition of alloy. After the fall, stress restores to the initial value (see figure 2). A calculation with the expansion coefficient \( \Delta l_T = \alpha \times l_0 \times \Delta T \) leads to other values that pertain in the interval \( 1.44 \times 10^{-5} \text{ m} - 6.84 \times 10^{-5} \text{ m} \) depending on the composition of alloy.

The calculated values have been presented in table 2.

| Alloy    | Lengthens calculated by Hooke’s law  | Lengthens calculated by the law of thermal expansion |
|----------|--------------------------------------|----------------------------------------------------|
|          | \( \Delta l_y \times 10^{-5} \), for  | \( \Delta l_T \times 10^{-5} \), for               |
|          | \( \Delta \sigma = 200 \) MPa        | \( \Delta \sigma = 400 \) MPa                     |
|          | MPa                                  | \( \Delta \sigma = 600 \) MPa                     |
| AMAG-170 | 18.38                                | 1.82                                               |
|          | 36.72                                | 3.96                                               |
|          | 55.15                                | 5.97                                               |
| AMAG-172 | 17.42                                | 1.82                                               |
|          | 34.85                                | 3.96                                               |
|          | 52.27                                | 6.12                                               |
| AMAG-179 | 16.07                                | 1.62                                               |
|          | 32.14                                | 3.87                                               |
|          | 48.21                                | 5.4                                                |
| AMAG-180 | 12.7                                 | 1.44                                               |
|          | 25.47                                | 2.97                                               |
|          | 38.21                                | 4.77                                               |
| AMAG-183 | 17.12                                | 1.89                                               |
|          | 34.25                                | 4.23                                               |
|          | 51.37                                | 6.84                                               |
| AMAG-186 | 15.26                                | 1.82                                               |
|          | 30.53                                | 3.6                                                |
|          | 45.8                                 | 5.58                                               |

A part of the reversible elongation of the specimen and, consequently, the value of the reversible fall of mechanical stress, caused thermal expansion, reach to ~ 11% from the whole elongation. It follows from the received results that additional changing of length exceeds the value, received from thermal expansion, on 78% in the total fall of mechanical stress. It testifies about that other reversible processes that are responsible for the falling of the mechanical stress occur except thermal expansion. For example, there are rival processes of the directed structural relaxation that can be reversible at the initial stage and the processes of the topological ordering and, the most probably, those all can be responsible for that behaviour of the mechanical stress in mentioned materials.

4. Conclusion
Thus, it has been established that the deformation rate does not significantly impact on mechanical parameters of amorphous metallic alloys (Young’s modulus and tensile strength do not change). The linear relationship between mechanical stress and furnace heating is observed depending on the composition of the alloy. Reversible fall of mechanical stress, received by the synergistic impact of the electrical impulses and mechanical stress, depends on elemental composition in amorphous alloy, and it is caused not only by thermal expansion but coursing of other processes, occurring by the impact on amorphous alloys, and, particularly, by the structural relaxation that is reversible at the initial stage. The received results permit to develop the exploitation regimes for the products from amorphous metallic alloys without changing of their mechanical properties.

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