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Chapter

Introductory Chapter: Metallic Glasses

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1. Introduction

Fast-growing technological development imposes a need for new functional materials with improved physical and mechanical properties. Since their first synthesis in 1960 [1], amorphous alloys, also known as metallic glasses, have been a focus of numerous investigations due to their advanced mechanical, electrical, magnetic, and anti-corrosion properties, related to their isotropic structure and short-range atomic arrangement [2–6].

Generally speaking, metallic glasses are multi-component systems involving different metals (M_I-M_{II}) or metal and non-metal, i.e., metalloid (M-NM) components [7–9]. For the M_I-M_{II} systems, the metals belong to the groups of transition, rare-earth or alkaline metals, or are uranium, neptunium, or plutonium [2, 10, 11]. The M-NM systems can be represented by the general formula $M_{75–85}NM_{15–25}$ (at.%), where M is one or more metal elements, usually the transition or noble one, and NM is one or more metalloid or non-metal elements, most commonly B, Si, Ge, C, or P.

The metallic glasses are solid materials without structural translational periodicity, characteristic for a crystalline structure. From the atomic aspect, the structure of metallic glasses is analogous to the structure of liquids, characterized by macroscopic isotropy, nonexistence of the long-range atomic ordering, but existence of a short-range ordering at the atomic level. The short-range ordering of the atoms means that each atom is surrounded by the same atoms positioned at similar distances, where the lines drawn between the atom centers form similar angles, as a consequence of chemical bonds keeping the atoms together in solid state. Variation in inter-atomic distances and angles means the variation in the strength of chemical bonds, causing the softening of material in defined temperature interval instead of melting at defined temperature [12].

The ability of a liquid alloy to transform into the metallic glass is called the glass-forming ability (GFA). The GFA is determined by structural, thermodynamic, and kinetic parameters characterizing the system, i.e., chemical composition, geometrical arrangement of atoms, bonding and atomic size effects, cooling rate, and crystallization kinetics [5]. So far, many empirical criteria were proposed with the aim of predicting and explaining the GFA [5, 13–15]. The empirical criteria for easier glass formation can be expressed in five points as follows:

1. alloy is multi-component containing at least three elements, two of which are metals;

2. atomic radii difference among the three constituent elements should be at least 12%;

3. heats of mixing among the main three elements should be negative;

4. total content of non-metals (metalloids) amounts to around 20 at.%; and

5. heteronucleants (oxide crystal inclusions) must be removed.

Generally speaking, the metallic glasses are solid materials exhibiting all the important features of the solid state. However, the short-range ordered glassy structure is manifested by broad halo peaks in XRD patterns. Due to the macroscopic isotropy of amorphous materials, for the description of their atomic structure, radial distribution function can be used. It represents the average number density of atoms as a function of the distance from the chosen atom.

In order to explain the amorphous structure of metallic glasses, different models were proposed [16–20]. Bernal introduced the model of dense random packing of hard spheres (DRPHS) [16, 17], which includes the presence of only metal atoms in the structure. The Polk's modification of the Bernal's model positioned the metalloid atoms at the larger holes of the DRPHS structure, but gave satisfactory results only for B and C as non-metallic components [18]. On the other hand, according to Gaskell's model [19], the alloy structure is built from the ordered structural units composed of 200–400 atoms, identified as trigonal prisms, tetrahedra, or octahedra, forming random long-range structures. In spite of a relatively large number of the proposed models and their modifications, many details related to the structure of amorphous alloys still remain unclear.

The term "metallic glasses" denotes those amorphous alloys obtained by rapid quenching techniques. During fabrication of a glassy alloy, the crystallization, including the steps of nucleation and growth of the formed nuclei, must be avoided. This can be achieved in different ways, involving very fast cooling of an alloy melt, often at a rate of 10^6 K min^{-1}. The most frequently used amorphization procedures aimed at preparation of amorphous alloys include rapid quenching of a melt of appropriate chemical composition, most commonly on a cold rotating metal disc [21]. Cooling rate necessary for amorphization is determined by the chemical composition, i.e., by the nature of the components forming a melt [8, 14]. Other methods used to obtained amorphous alloys include vapor deposition [22], spray deposition [23], ion implantation [24], laser processing [25], chemical reduction [26], electrodeposition [27], mechanical alloying [28], etc.

Glassy state is structurally and thermodynamically metastable and prone to transformations under the conditions of elevated pressure or temperature, or even during prolonged usage at moderate temperature. They could occur through the processes of relaxation, partial or complete crystallization, and recrystallization, changing the microstructure of a material, providing a simple procedure for production of polycrystalline and composite materials with targeted properties. Crystallization process can be [6, 12]:

- polymorphous crystallization (amorphous phase transforms into a single crystalline phase without a change in composition);

- primary crystallization (composition of the first crystalline phase formed from the glass differs from that of the amorphous matrix, and then the crystals of the phase formed primarily serve as the sites of secondary and tertiary crystallization);

- eutectic crystallization (two different phases crystallize simultaneously, in a coupled fashion, and their overall composition does not differ from that of the glassy matrix).

The microstructural transformations show a significant impact on physical properties of the materials changing their functionality. Structural relaxation process preceding the crystallization, characteristic of metallic glasses, includes rearrangement of individual species on the atom level and decrease in free volume, changing the short-range order and influencing primarily their electrical and magnetic properties. Additionally, as a result of relaxation, density, elastic modulus, Curie temperature, and viscosity grow, while thermal resistivity, diffusivity, and fracture toughness decrease [12]. The relaxation process can be achieved by low-temperature annealing at temperatures below the crystallization temperature.

Partial crystallization of metallic glasses leads to the formation of nanostructured or composite materials, involving nanocrystals embedded in amorphous matrix, with specific physical properties. All these together make the metallic glasses extraordinary precursors for the production of materials with targeted functionality. Properties of metallic glasses and nanocrystalline alloys obtained from the amorphous precursors are determined by both, the alloy chemical composition and microstructure.

Almost all the glassy alloys with favorable magnetic properties contain a high percentage of transition metals or rare earth elements. In this sense, iron, cobalt, and nickel-based metallic glasses are soft magnetic materials. Their excellent combination of magnetic properties including low coercivity, relatively high saturation magnetization, zero magnetostriction as well as their relatively high electrical resistivity allows their application in transformer cores, magnetic sensors, magnetic shielding, amplifiers, information handling technologies [6, 29, 30], etc. On the other hand, addition of Nd and Pr provides their hard magnetic properties [31].

Metallic glasses are considered, from a mechanical point of view, very hard and strong materials, with high wear resistance [2, 6]. The high strength of these materials is a consequence of the fact that they do not contain defects characteristic for crystalline structure. Advantageous mechanical properties are exhibited by the multi-component alloys based on Ti, Zr, Al, Mg, Fe, Co, or Ni [5, 32–40]. However, these materials are characterized by limited plastic strain in tension, while the inhomogeneous deformation occurs through the formation of shear bands [6]. Fracture toughness of metallic glasses is somewhat lower than that of crystalline materials, but two orders of magnitude higher than in the case of oxide glasses [12]. Metallic glasses based on Al and Mg possess high specific strength, due to their low density and mass [39, 40]. As a result of their favorable mechanical properties, including high strength and large elastic elongation limit, metallic glasses are used in reinforcing composites, for sporting goods, microgears, aircraft parts, brazing foils [6, 12, 41, 42], etc.

Good corrosion resistance, observed for the metallic glasses containing Cr, Zr, Ni, Nb, Mo, or V, is a particularly important characteristic of these materials from the aspect of their applicability in modern technology [43–46]. Some metallic glasses are suitable for being used as biomedical materials (such as the TiZrCuPdSn alloys [47]), while some other glassy alloys show superconducting properties (such as the TiNb-based ones [48]).

From a technological point of view, nanocrystalline alloys obtained by partial crystallization of the glassy alloys represent a particularly interesting class of functional materials. The iron-based nanocrystalline alloys with the composition Fe-R-B (where R is rare earth element, B is boron) possess hard magnetic properties [49]. However, the soft magnetic materials in this class are nanocrystalline materials with the composition Fe-Si-B-Nb-Cu (FINEMET), Fe-M-B-Cu (M is Zr, Hb or F) (NANOPERM), Fe-Co-M-B-Cu (M is Zr, Hb or F) (HITPERM) [50], etc. To maintain favorable functional properties, in this case the soft magnetic ones, crystal size of the α-Fe or α-Fe(Si) in FINEMET or NANOPERM alloys must not exceed 15 nm [51]. To obtain nanocrystalline structure from the amorphous one, controlled fast nucleation and slow crystal growth are required. This can be achieved by an appropriate choice of the alloy composition and by thermal treatment as in the FINEMET-type alloys, where Cu is added to facilitate nucleation, while the Nb decreases the crystal growth rate [51–53].

In order to provide and maintain an amorphous or nanocrystalline structure of targeted functionality, thermal stability, thermodynamics, and kinetics of phase transformations thermally induced of amorphous and nanocrystalline materials should be known [8, 54–75]. This requires determination of the temperatures of all of the phase transformations as well as the kinetic triplets of these processes, consisting of Arrhenius parameters, activation energy, and pre-exponential factor, as well as kinetic model (conversion function). By determining the crystallization kinetic model, information about crystallization mechanism, including nucleation, crystal growth, and impingement effects can be obtained. In this way, the lifetime of specific microstructure, important for reliable applicability of materials, can be predicted.

Solid-state transformations are often complex processes, consisting of several concurrent or consecutive steps, manifested experimentally by compounded curve forms. In order to discuss all these steps and propose the most probable mechanisms, during the analysis, deconvolution of the compounded peaks (DSC, TG, or even XRD) by using different mathematical tools is required [76–84].

In view of the foregoing, metallic glasses have still been intriguing although studied for more than 50 years now, offering a wide range of practical applications either in the glassy or derivative form, and promising further technological improvement and development.

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References

[1] Klement W, Willens RH, Duwez P. Non-crystalline structure in solidified gold–silicon alloys. Nature. 1960;**187**: 869-870

[2] Suryanarayana C. Metallic glasses. Bulletin of Materials Science. 1984;**6**:579-594

[3] Flohrer S, Herzer G. Random and uniform anisotropy in soft magnetic nanocrystalline alloys. Journal of Magnetism and Magnetic Materials. 2010;**322**:1511-1514

[4] Zarebidaki A, Seifoddini A, Rabizadeh T. Corrosion resistance of $Fe_{77}Mo_5P_9C_{7.5}B_{1.5}$ in-situ metallic glass matrix composites. Journal of Alloys and Compounds. 2018;**736**:17-21

[5] Suryanarayana C, Inoue A. Iron-based bulk metallic glasses. International Materials Review. 2013;**58**:131-166

[6] Suryanarayana C, Inoue A. Metallic glasses. In: Ullmann's Encyclopedia of Industrial Chemistry. Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA; 2012

[7] Hasegawa R, O'Handley RC, Tanner LE, Ray R, Kavesh S. Magnetization, magnetic anisotropy, and domain patterns of $Fe_{80}B_{20}$ glass. Applied Physics Letters. 1976;**29**:219-221

[8] Kaloshkin SD, Tomilin IA. The crystallization kinetics of amorphous alloys. Thermochimica Acta. 1996;**280/281**:303-317

[9] Mendelsohn L, Nesbitt E, Bretts G. Glassy metal fabric: A unique magnetic shield. IEEE Transactions on Magnetics. 1976;**12**:924-926

[10] Nassif E, Lamparter P, Sperl W, Steeb S. Structural investigation of the metallic glasses $Mg_{85.5}Cu_{14.5}$ and $Mg_{70}Zn_{30}$. A Journal of Physical Sciences. 1983;**38a**:142-148

[11] Korelis PT, Liebig A, Bjorck M, Hjorvarsson B, Lidbaum H, Leifer K, et al. Highly amorphous $Fe_{90}Zr_{10}$ thin films, and the influence of crystallites on the magnetism. Thin Solid Films. 2010;**519**:404-409

[12] Shiflet GJ, Leng Y, Hawk JW. Metallic glasses. In: Ullmann's Encyclopedia of Industrial Chemistry. Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA; 2005

[13] Chen HS. Glassy metals. Reports on Progress in Physics. 1980;**43**:353-432

[14] Turnbull D. Under what conditions can a glass be formed. Contemporary Physics. 1969;**10**:473-488

[15] Egami T, Waseda Y. Atomic size effect on the formability of metallic glasses. Journal of Non-Crystalline Solids. 1984;**64**:113-134

[16] Finney JL. Short-range structure of amorphous alloys. Nature. 1979;**280**:847-847

[17] Bernal JD. The Bakerian Lecture, 1962, The structure of liquids. Proceedings of the Royal Society of London A. 1964;**280**:299-320

[18] Polk DE. The structure of glassy metallic alloys. Acta Metallurgica. 1972;**20**:485-491

[19] Gaskell PH. A new structural model for amorphous transition metal silicides, borides, phosphides and carbides. Journal of Non-Crystalline Solids. 1979;**32**:207-224

[20] Greer AL. Metallic glasses... on the threshold. Materials Today. 2009;**12**:14-22

[21] Budhani RC, Goel TC, Chopra KL, Chopra KL. Melt-spinning technique for preparation of metallic glasses. Bulletin of Materials Science. 1982;**4**:549-561

[22] Mader S, Nowick AS. Metastable Co-Au alloys: Example of an amorphous ferromagnet. Applied Physics Letters. 1965;**7**:57-59

[23] Moss M, Smith DL, Lefever RA. Metastable phases and superconductors produced by plasma-jet spraying. Applied Physics Letters. 1964;**5**:120-121

[24] Grant WA. Amorphous metals and ion implantation. Journal of Vacuum Science and Technology. 1978;**15**:1644-1649

[25] Breinan EM, Kear BH, Banas CM. Processing materials with lasers. Physics Today. 1976;**29**:44-50

[26] Wonterghem J, Mørup S, Koch CJW, Charles SW, Wells S. Formation of ultra-fine amorphous alloy particles by reduction in aqueous solution. Nature. 1986;**322**:622-623

[27] Eliaz N, Sridhar TM, Gileadi E. Synthesis and characterization of nickel tungsten alloys by electrodeposition. Electrochimica Acta. 2005;**50**:2893-2904

[28] Koch CC, Cavin OB, McKamey CG, Scarbrough JO. Preparation of "amorphous" $Ni_{60}Nb_{40}$ by mechanical alloy. Applied Physics Letters. 1983;**43**:1017-1019

[29] Hasegawa R. Soft magnetic properties of metallic glasses. Journal of Magnetism and Magnetic Materials. 1984;**41**:79-85

[30] Hernando A, Vázquez M, Barandiarán JM. Metallic glasses and sensing applications. Journal of Physics E. 1988;**21**:1129-1139

[31] Inoue A, Zhang T, Takeuchi A. Hard magnetic bulk amorphous alloys. IEEE Transactions on Magnetics. 1997;**33**:3814-3816

[32] Jang D, Gross CT, Greer JR. Effects of size on the strength and deformation mechanism in Zr-based metallic glasses. International Journal of Plasticity. 2011;**27**:858-867

[33] Inoue A, Zhang W, Zhang T. Thermal stability and mechanical strength of bulk glassy Ni–Nb–Ti–Zr Alloys. Materials Transactions. 2002;**43**:1952-1956

[34] Wang J, Li R, Xiao R, Xu T, Li Y, Liu Z, et al. Compressibility and hardness of Co-based bulk metallic glass: A combined experimental and density functional theory study. Applied Physics Letters. 2011;**99**:151911

[35] Ma C, Istihara S, Soejima H, Nishiyama N, Inoue A. Formation of new Ti-based metallic glassy alloys. Materials Transactions. 2004;**45**:1802-1806

[36] Blagojević VA, Vasić M, David B, Minić DM, Pizúrová N, Žák T, et al. Microstructure and functional properties of $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ amorphous alloy. Materials Chemistry and Physics. 2014;**145**:12-17

[37] Blagojević VA, Minić DM, Žák T, Minić DM. Influence of thermal treatment on structure and microhardness of $Fe_{75}Ni_2Si_8B_{13}C_2$ amorphous alloy. Intermetallics. 2011;**19**:1780-1785

[38] Minić DM, Blagojević VA, Minić DM, Gavrilović A, Rafailović L, Žák T. Influence of microstructure on microhardness of $Fe_{81}Si_4B_{13}C_2$ amorphous alloy after thermal treatment. Metallurgical and Materials Transactions A. 2011;**42A**:4106-4112

[39] Inoue A, Matsumoto N, Masumoto T. Al–Ni–Y–Co amorphous alloys with high mechanical strengths, wide supercooled liquid region and large glass-forming capacity. Materials Transactions, JIM. 1990;**31**:493-500

[40] Inoue A, Masumoto T. Mg-based amorphous alloys. Materials Science and Engineering A. 1993;**173**:1-8

[41] Dudina DV, Georgarakis K, Li Y, Aljerf M, LeMoulec A, Yavari AR, et al. A magnesium alloy matrix composite reinforced with metallic glass. Composites Science and Technology. 2009;**69**:2734-2736

[42] Ashby MF, Greer AL. Metallic glasses as structural materials. Scripta Materialia. 2006;**54**:321-326

[43] Tenhover MA, Lukco DB, Shreve GA, Henderson RS. Corrosion resistance of Cr-based amorphous metal alloys. Journal of Non-Crystalline Solids. 1990;**116**:233-246

[44] Qin FX, Zhang HF, Deng YF, Ding BZ, Hu ZQ. Corrosion resistance of Zr-based bulk amorphous alloys containing Pd. Journal of Alloys and Compounds. 2004;**375**:318-323

[45] Rife G, Chan PCC, Aust KT. Corrosion of iron-, nickel- and cobalt-base metallic glasses containing boron and silicon metalloids. Materials Science and Engineering. 1981;**48**:73-79

[46] Ma H, Wang W, Zhang J, Li G, Cao C, Zhang H. Crystallization and corrosion resistance of $(Fe_{0.78}Si_{0.09}B_{0.13})_{100-x}Ni_x$ (x = 0, 2 and 5) glassy alloys. Journal of Materials Science and Technology. 2011;**27**:1169-1177

[47] Zhu SL, Wang XM, Inoue A. Glass-forming ability and mechanical properties of Ti-based bulk glassy alloys with large diameters of up to 1 cm. Intermetallics. 2008;**16**:1031-1035

[48] Inoue A, Masumoto T, Suryanarayana C, Hoshi A. Superconductivity of ductile titanium-niobium-based amorphous alloys. Journal de Physique, Colloque. 1980;**41**:C8758-C8761

[49] Yang CJ, Ray R, O'Handley RC. Magnetic hardening in melt-spun Fe-R-B alloys. Materials Science and Engineering. 1988;**99**:137-141

[50] McHenry ME, Willard MA, Laughlin DE. Amorphous and nanocrystalline materials for applications as soft magnets. Progress in Materials Science. 1999;**44**:291-433

[51] Kulik T. Nanocrystallization of metallic glasses. Journal of Non-Crytalline Solids. 2001;**287**:145-161

[52] Hono K, Ping DH, Ohnuma M, Onodera H. Cu clustering and Si partitioning in the early crystallization stage of an $Fe_{73.5}Si_{13.5}B_9Nb_3Cu_1$ amorphous alloy. Acta Materialia. 1999;**47**:997-1006

[53] Zhang YR, Ramanujan RV. The effect of niobium alloying additions on the crystallization of a Fe–Si–B–Nb alloy. Journal of Alloys and Compounds. 2005;**403**:197-205

[54] Tkatch VI, Limanovskii AI, Kameneva VY. Studies of crystallization kinetics of $Fe_{40}Ni_{40}P_{14}B_6$ and $Fe_{80}B_{20}$ metallic glasses under non-isothermal conditions. Journal of Materials Science. 1997;**32**:5669-5677

[55] Xu D, Johnson WL. Crystallization kinetics and glass-forming ability of bulk metallic glasses $Pd_{40}Cu_{30}Ni_{10}P_{20}$ and $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ from classical theory. Physical Review B. 2006;**74**:024207

[56] Wang Y, Zhai H, Li Q, Liu J, Fan J, Li Y, et al. Effect of Co substitution for Fe on the non-isothermal crystallization kinetics of $Fe_{80}P_{13}C_7$ bulk metallic glasses. Thermochimica Acta. 2019;**675**:107-112

[57] Gavrilović A, Rafailović LD, Minić DM, Wosik J, Angerer P, Minić DM. Influence of thermal treatment on structure development and mechanical properties of amorphous $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ ribbon. Journal of Alloys and Compounds. 2011;**509S**:S119-S122

[58] Vasić MM, Surla R, Minić DM, Lj R, Mitrović N, Maričić A, et al.

Thermally induced microstructural transformations of $Fe_{72}Si_{15}B_8V_4Cu_1$ alloy. Metallurgical and Materials Transactions A. 2017;**48A**:4393-4402

[59] Gavrilović A, Minić DM, Rafailović LD, Angerer P, Wosik J, Maričić A, et al. Phase transformations of $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ amorphous alloy upon thermal treatment. Journal of Alloys and Compounds. 2010;**504**:462-467

[60] Blagojević VA, Vasić M, David B, Minić DM, Pizúrová N, Žák T, et al. Thermally induced crystallization of $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ amorphous alloy. Intermetallics. 2014;**45**:53-59

[61] Minić DM, Blagojević VA, Maričić AM, Žák T, Minić DM. Influence of structural transformations on functional properties of $Fe_{75}Ni_2Si_8B_{13}C_2$ amorphous alloy. Materials Chemistry and Physics. 2012;**134**:111-115

[62] Minić DM, Blagojević VA, David B, Pizúrová N, Žák T, Minić DM. Influence of thermal treatment on microstructure of $Fe_{75}Ni_2Si_8B_{13}C_2$ amorphous alloy. Intermetallics. 2012;**25**:75-79

[63] Minić DM, Gavrilović A, Angerer P, Minić DG, Maričić A. Structural transformations of $Fe_{75}Ni_2Si_8B_{13}C_2$ amorphous alloy induced by thermal treatment. Journal of Alloys and Compounds. 2009;**476**:705-709

[64] Minić DM, Blagojević VA, Minić DM, David B, Pizúrová N, Žák T. Nanocrystal growth in thermally treated $Fe_{75}Ni_2Si_8B_{13}C_2$ amorphous alloy. Metallurgical and Materials Transactions A. 2012;**43A**:3062-3069

[65] Minić DM, Minić DM, Žák T, Roupcová P, David B. Structural transformations of $Fe_{81}B_{13}Si_4C_2$ amorphous alloy induced by heating. Journal of Magnetism and Magnetic Materials. 2011;**323**:400-404

[66] Minić DM, Minić DG, Maričić A. Stability and crystallization of $Fe_{81}B_{13}Si_4C_2$ amorphous alloy. Journal of Non-Crystalline Solids. 2009;**355**:2503-2507

[67] Blagojević VA, Minić DM, Vasić M, Minić DM. Thermally induced structural transformations and their effect on functional properties of $Fe_{89.8}Ni_{1.5}Si_{5.2}B_3C_{0.5}$ amorphous alloy. Materials Chemistry and Physics. 2013;**142**:207-212

[68] Kuo YC, Zhang LS, Zhang WK. The crystallization kinetics of amorphous $Co_{78-x}Fe_xSi_8B_{14}$ ribbons. Journal of Applied Physics. 1981;**52**:1889-1891

[69] Yuan ZZ, Chen XD, Wang BX, Chen ZJ. Crystallization kinetics of melt-spun $Co_{43}Fe_{20}Ta_{5.5}B_{31.5}$ amorphous alloy. Journal of Alloys and Compounds. 2005;**399**:166-172

[70] Bayri N, Kolat VS, Izgi T, Atalay S, Gencer H, Sovak P. Crystallisation kinetics of $Co_{75-x}M_xSi_{15}B_{10}$ (M = Fe, Mn, Cr and x = 0, 5) amorphous alloys. Acta Physica Polonica A. 2016;**129**:84-87

[71] Jung HY, Stoica M, Yi S, Kim DH, Eckert J. Crystallization kinetics of $Fe_{76.5-x}C_{6.0}Si_{3.3}B_{5.5}P_{8.7}Cu_x$ (x = 0, 0.5, and 1 at. pct) bulk amorphous alloy. Metallurgical and Materials Transactions A. 2015;**46**:2415-2421

[72] Gharsallah HI, Sekri A, Azabou M, Escoda L, Suñol JJ, Khitouni M. Structural and thermal study of nanocrystalline Fe-Al-B alloy prepared by mechanical alloying. Metallurgical and Materials Transactions A. 2015;**46**:3696-3704

[73] Dong Q, Pan YJ, Tan J, Qin XM, Li CJ, Gao P, et al. A comparative study of glass-forming ability, crystallization kinetics and mechanical properties of $Zr_{55}Co_{25}Al_{20}$ and $Zr_{52}Co_{25}Al_{23}$ bulk metallic glasses. Journal of Alloys and Compounds. 2019;**785**:422-428

[74] Lozada-Flores O, Figueroa IA, Gonzalez G, Salas-Reyes AE. Influence of minor additions of Si on the crystallization kinetics of $Cu_{55}Hf_{45}$ metallic glasses. Thermochimica Acta. 2018;**662**:116-125

[75] Bizhanova G, Li F, Ma Y, Gong P, Wang X. Development and crystallization kinetics of novel near-equiatomic high-entropy bulk metallic glasses. Journal of Alloys and Compounds. 2019;**779**:474-486

[76] Vasić MM, Žák T, Pizúrová N, Roupcová P, Minić DM, Minić DM. Thermally induced microstructural transformations and anti-corrosion properties of $Co_{70}Fe_5Si_{10}B_{15}$ amorphous alloy. Journal of Non-Crystalline Solids. 2018;**500**:326-335

[77] Vasić MM, Blagojević VA, Begović NN, Žák T, Pavlović VB, Minić DM. Thermally induced crystallization of amorphous $Fe_{40}Ni_{40}P_{14}B_6$ alloy. Thermochimica Acta. 2015;**614**:129-136

[78] Vasić MM, Minić DM, Blagojević VA, Minić DM. Kinetics and mechanism of thermally induced crystallization of amorphous $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ alloy. Thermochimica Acta. 2014;**584**:1-7

[79] Blagojević VA, Vasić M, Minić DM, Minić DM. Kinetics and thermodynamics of thermally induced structural transformations of amorphous $Fe_{75}Ni_2Si_8B_{13}C_2$ alloy. Thermochimica Acta. 2012;**549**:35-41

[80] Vasić M, Minić DM, Blagojević VA, Minić DM. Mechanism and kinetics of crystallization of amorphous $Fe_{81}B_{13}Si_4C_2$ alloy. Thermochimica Acta. 2013;**572**:45-50

[81] Vasić M, Minić DM, Blagojević VA, Minić DM. Mechanism of thermal stabilization of $Fe_{89.8}Ni_{1.5}Si_{5.2}B_3C_{0.5}$ amorphous alloy. Thermochimica Acta. 2013;**562**:35-41

[82] Wang Y, Xu K, Li Q. Comparative study of non-isothermal crystallization kinetics between $Fe_{80}P_{13}C_7$ bulk metallic glass and melt-spun glassy ribbon. Journal of Alloys and Compounds. 2012;**540**:6-15

[83] Cole KM, Kirk DW, Singh CV, Thorpe SJ. Role of niobium and oxygen concentration on glass forming ability and crystallization behavior of Zr-Ni-Al-Cu-Nb bulk metallic glasses with low copper concentration. Journal of Non-Crystalline Solids. 2016;**445-446**:88-94

[84] Kotrlova M, Zeman P, Zuzjakova S, Zitek M. On crystallization and oxidation behavior of $Zr_{54}Cu_{46}$ and $Zr_{27}Hf_{27}Cu_{46}$ thin-film metallic glasses compared to a crystalline $Zr_{54}Cu_{46}$ thin-film alloy. Journal of Non-Crystalline Solids. 2018;**500**:475-481