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ADVANCED HIGH-STRENGTH AND DUCTILE Fe-Cr-Mo-Ga-Si ALLOYS

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Abstract. Two crystalline Fe-Cr-Mo-Ga-Si alloys were prepared by copper mold casting using various types of crucible materials. The materials were derived from a bulk metallic glass-forming composition with the aim to enhance the ductility of this high-strength alloy. The rods obtained under different conditions show significantly varying microstructures and mechanical properties. The best mechanical characteristics were found for samples, which essentially consist of ductile Ga-rich dendrites dispersed in high-strength Cr- and Mo-rich interdendritic phase(s). The combination of the soft and hard phases results in a composite material with high fracture strength (about 3 GPa) connected with very good plasticity (up to 13%). The discovery of new high-strength Fe-based materials with a good deformability is an important step ahead for the further development of Fe-based alloys as engineering materials.

1. INTRODUCTION

Bulk metallic glasses (BMGs) are currently the subject of intense investigations due to their unique properties [1,2]. Among glass-forming alloy systems reported so far, Fe-based BMGs play a special role, because they show superior mechanical strength of 2.8 – 4.0 GPa [3-6]. However, their wider application as structural material is strongly limited because of their low macroscopic plasticity. In order to overcome this problem great efforts have been devoted to the fabrication of BMG composite materials. *In situ*-formed BMG composites display noticeable enhanced plasticity in comparison with their monolithic counterpart [7-9]. However, there is still a lack of such composite formation for ferrous alloy systems. This paper presents investigations on the phase formation and the mechanical behavior of two novel Fe-based alloys. Their compositions were derived from the $Fe_{65.5}Cr_4Mo_4Ga_4P_{12}C_5B_{5.5}$ BMG [10] by substitution of the metalloids (P, C, B) and addition of Si. Despite the low glass-forming ability of the quinary Fe-Cr-Mo-Ga-Si alloy system, which is not sufficient to obtain the glassy structure by copper mold casting, excellent mechanical characteristics were found for examined crystalline materials.

2. EXPERIMENTAL PROCEDURE

The alloys presented with nominal composition $Fe_{81.1}Cr_{5.2}Mo_{5.2}Ga_{5.2}Si_{3.2}$ (A) and $Fe_{78.0}Cr_{5.2}Mo_{5.2}Ga_{5.2}Si_{6.4}$ (B) were fabricated by arc-melting. The rod-shaped samples with a diameter of 3 mm and a length of 6 mm were produced by centrifugal copper mold casting, using two different crucible materials: Al_2O_3 and glass carbon (GC). The C content was additionally measured for the

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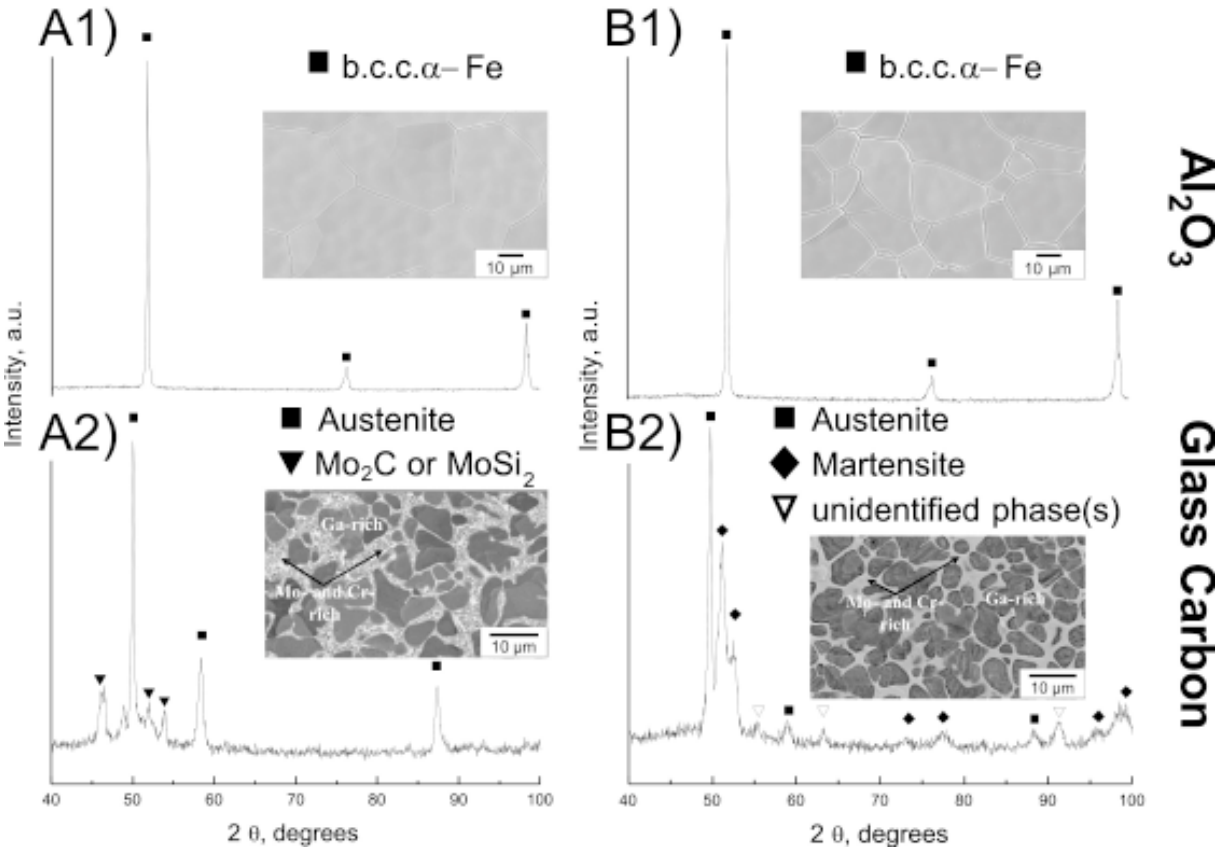


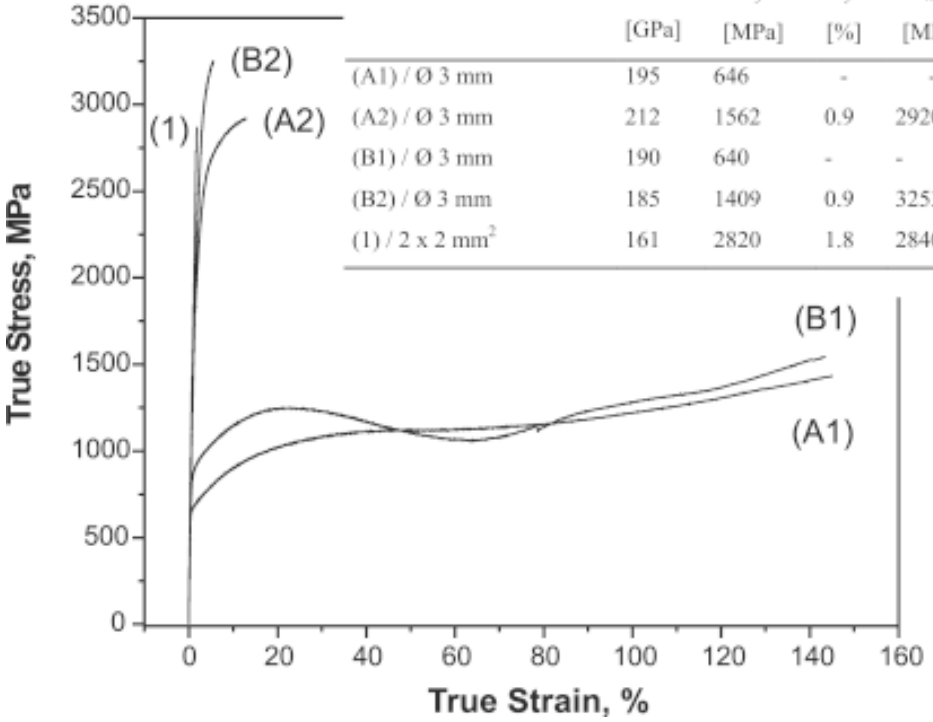
Fig. 1. XRD patterns for as-cast alloy A ($Fe_{81.1}Cr_{5.2}Mo_{5.2}Ga_{5.2}Si_{3.2}$) and alloy B ($Fe_{78.0}Cr_{5.2}Mo_{5.2}Ga_{5.2}Si_{6.4}$) prepared by using an Al_2O_3 crucible (A1 and B1) and by using a glass carbon crucible (A2 and B2). In addition, the corresponding SEM micrographs of the microstructures of the studied rod samples are shown. The microstructure of alloy A2 and alloy B2 consists of micro-sized Ga-enriched dendrites (as denoted by white arrows) embedded in Mo- and Cr-enriched interdendritic phase(s) (as denoted by black arrows).

samples prepared in the glass carbon crucible to 3.33 wt.% for the alloy with lower Si content (A) and 1.54 wt.% for the alloy with higher Si content (B), respectively.

The microstructure of the as-prepared samples was analyzed by X-ray diffraction (XRD) with Co-Kα radiation and scanning electron microscopy (SEM) equipped with EDX and WDX spectroscopy. The mechanical behavior of the alloys was measured by room temperature compression tests and Vickers hardness tests. Compression measurements were performed using an electromechanical Instron 8562 testing device under quasistatic loading (strain rate $1 \cdot 10^{-4}$ s^{-1}). From the cast rods cylindrical samples with Ø 3 mm×6 mm length were prepared. The Vickers hardness was evaluated using a Struers Duramin 5 hardness tester. Loads of 4.9 N and 9.8 N were applied for 10 s.

3. RESULTS AND DISCUSSION

Fig. 1 displays the XRD patterns of the investigated samples corresponding to two different compositions (A+B) and to various preparation conditions, i.e. two different crucible materials (Al_2O_3+GC). Additionally, the corresponding SEM images of the microstructures of these four as-cast states are shown. The obtained XRD patterns (Fig. 1) clearly indicate that different processing routes applied cause significant differences in the microstructure of the samples. A1 and B1 (Al_2O_3 crucible) exhibit a single-phase structure, while the rods prepared



alloy/sample dimensions	true values				
	E [GPa]	σ_y [MPa]	ε_y [%]	σ_{max} [MPa]	ε_f [%]
(A1) / Ø 3 mm	195	646	-	-	> 140
(A2) / Ø 3 mm	212	1562	0.9	2920	13
(B1) / Ø 3 mm	190	640	-	-	> 140
(B2) / Ø 3 mm	185	1409	0.9	3253	6
(1) / 2 x 2 mm^2	161	2820	1.8	2840	1.9

Fig. 2. Room temperature true stress-strain curves of $Fe_{81.1}Cr_{5.2}Mo_{5.2}Ga_{5.2}Si_{3.2}$ – A1 (Al_2O_3); A2 (GC), $Fe_{78.0}Cr_{5.2}Mo_{5.2}Ga_{5.2}Si_{6.4}$ – B1 (Al_2O_3); B2 (GC) and $Fe_{65.5}Cr_4Mo_4Ga_4P_{12}C_5B_5$ (BMG) – (C) alloys subjected to the compression deformation.

by using GC crucible are composed of a mixture of phases. A1 and B1 reveal the formation of a b.c.c. (body-centered cubic) α-Fe solid solution. In case of sample A2 the main peaks can be assigned to a f.c.c. (face-centered cubic) austenitic phase (γ-Fe). Additional visible reflections correspond either to a hexagonal (hP3) Mo_2C phase or a $MoSi_2$ phase. The microstructure of alloy B2 is mainly composed of a b.c.t. (body-centered tetragonal) martensitic phase and a Cr_3Si phase. Additional weaker reflections belong to one or more unknown crystalline phases. Obviously, differences in the microstructure of studied samples (A1+B1 and A2+B2) are due to C contamination, which diffuses from the crucible. The appearance of such element in the structure of as-cast alloys causes the considerable changes in the phase formation.

According to the XRD results noticeable dissimilarities in the phase formation for samples prepared under different conditions were observed. The upper images for samples A1 and B1 reveal a homogeneous structure (Fig. 1). In contrast, the microstructure of alloy A2 and alloy B2 manifests the composite nature of these samples consisting of a dendritic phase (dark phase) and a matrix (bright phase). WDX analysis has confirmed the presence of carbon in the microstructure of samples A2 and B2. C is mainly localized in the interdendritic phases, which are Cr- and Mo-enriched. Such constituents are well known for their tendency to form carbides.

Fig. 2 shows the room-temperature compressive true stress-strain curves of these as-cast states. In addition, the results reported by Stoica *et al*. for the $Fe_{65.5}Cr_4Mo_4Ga_4P_{12}C_5B_{5.5}$ bulk glassy alloy are shown for comparison. Mechanical properties derived from the performed measurements are summarized in table-inset in Fig. 2. The samples possessing a complex structure exhibit a very high strength of about $\sigma_{fracture}$ = 2.9 GPa (A2) and $\sigma_{fracture}$ = 3.3 GPa (B2). It is important to notice that these values are higher compared with the frac-

ture strength of Fe-based BMG ($\sigma_{fracture}$ = 2.8 GPa) [10]. Furthermore, there is a significant increase in the plasticity for the crystalline samples A2 and B2, $\varepsilon_{plastic}$ = 12% and $\varepsilon_{plastic}$ = 5%, respectively.

It has further been recognized that, compared to the composite samples (A2 and B2), the single-phase alloys A1 and B1 subjected to the compression loading manifest a significantly different deformation mode. Such alloys possess an amazing capacity for plastic deformation, ε > 140%. Based on these findings we can conclude that the appearance of the specific complex microstructure leads to a material with very high fracture strength and good ductility, while the formation of the single-phase structure results in extremely high plasticity of examined alloys. In order to determine the properties of particular phases, the hardness measurements were carried out for samples A2 and B2. According to WDX results we expected that differences in the C concentration between precipitates and matrix phase are reflected by their hardness. The investigated composites essentially consist of soft Ga-enriched precipitates ($HV_{A2,B2} \approx$ 4.2 GPa) embedded in a hard Cr- and Mo-enriched matrix ($HV_{A2} \approx$ 6.3 GPa and $HV_{B2} \approx$ 9.6 GPa). The values measured for the matrix are congenial with the hardness of the $Fe_{65.5}Cr_4Mo_4Ga_4P_{12}C_5B_{5.5}$ glassy alloy, $HV_{BMG} \approx$ 8.7 GPa. The coexistence of ductile precipitates with a high-strength matrix is responsible for the excellent mechanical properties observed.

4. CONCLUSIONS

Novel Fe-based alloys with high-strength and large plasticity were prepared by centrifugal casting technique. Considering the complexity of the alloys A2 and B2 it was found that the coexistence of a ductile dendritic phase with a high-strength matrix leads to a material with excellent mechanical properties. The values of fracture strength obtained for crystalline composite alloys A2 and B2 are similar to the fracture strength reported by Stoica *et al.* for monolithic $Fe_{65.5}Cr_4Mo_4Ga_4P_{12}C_5B_{5.5}$ BMG and the values of fracture strain are even significantly improved. Furthermore, variations in the C content in case of samples A2 and B2 (3.33 wt.% and 1.54 wt.%) cause differences in the ductility by a factor of two. In contrast, the apparent fracture strength is nearly the same. Completely different mechanical characteristics were found for the samples with a single-phase structure. These alloys exhibit an amazing capacity for compression deformation ε_f > 140%. Based on above-described findings we conclude that the discovery of new high-strength and ductile Fe-based composites is very promising for the further development of Fe-based alloys as engineering materials.

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