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Al-BASED ALLOYS CONTAINING AMORPHOUS AND NANOSTRUCTURED PHASES

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Abstract. Nanostructured or partially amorphous Al-based alloys are attractive candidates for advanced high-strength lightweight materials. The strength of such materials is often 2 – 3 times higher than the strength of commercial crystalline alloys. Further property improvements are achievable by designing multi-phase composite materials with optimized length scale and intrinsic properties of the constituent phases. Such alloys can be prepared by quenching from the melt or by powder metallurgy using mechanical attrition techniques. This paper focuses on mechanically attrited Al-based powders containing amorphous or nano-crystalline phases, Al-based MMCs containing metallic glass reinforcement and on their consolidation into bulk specimens. Selected examples of mechanical deformation behavior are presented, revealing that the properties can be tuned within a wide range of strength and ductility as a function of size and volume fraction of the different phases.

1. INTRODUCTION

The starting point for the development of new high-strength Al-alloys was the discovery of high tensile strength exceeding 1200 MPa for melt-spun Al-ETM-LTM amorphous ribbons [1]. Such strength levels are about twice as high as for conventional crystalline alloys. Another interesting material, consisting of a nanoscale phase mixture of quasicrystalline icosahedral particles coexisting with a ductile fcc Al phase, has been produced in various melt-spun Al-based ribbons [2]. This type of mixed structure exhibits good ductility and high room temperature tensile strength of about 1000 – 1340 MPa [2]: the quasicrystals act as strength-bearing component, while the Al matrix supplies ductility.

Although melt-spun ribbons exhibit an ultimate strength exceeding that of conventional Al alloys by a factor of 2 – 3 [3], their small size prevents engineering applications. For that reason, powder metallurgical methods such as gas atomization or mechanical attrition have been employed to create powder particles with the desired microstructure [3]. This approach presents two main problems: the production of the same material by a processing route different than liquid quenching and the subsequent consolidation of the powders into bulk specimens.

Accordingly, this paper will review some of our recent results on the production of high strength Al-based amorphous / nanostructured alloys that were synthesized by a combination of rapid quenching and mechanical attrition methods. Such nanostructured materials may contain crystalline, quasicrystalline or amorphous phases of the metallic constituents and their mechanical properties

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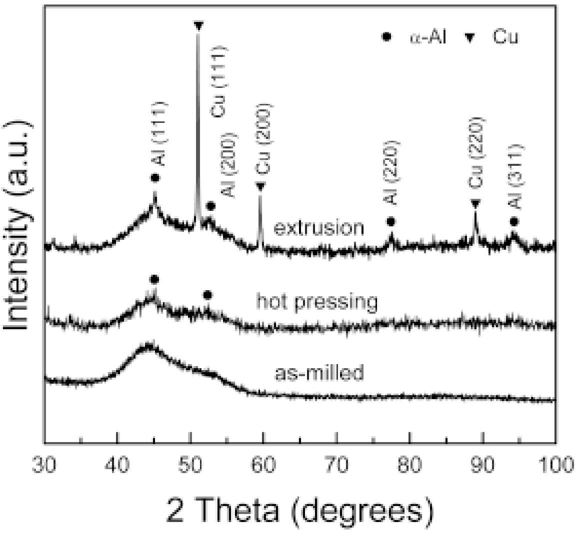

Fig. 1. XRD patterns of (a) as-milled powder and bulk samples after consolidation *via* (b) uniaxial hot pressing and (c) extrusion for the $Al_{85}Ni_9Nd_4Co_2$ alloy. (The Cu phase peaks stem from the Cu can used for encapsulation of the samples).

are very encouraging regarding the combination of high strength and good ductility at room temperature.

2. EXPERIMENTAL

Mechanically attrited powders from elemental powder mixtures as well as from melt-spun glassy ribbons were produced using a planetary ball mill and hardened steel balls and vials. All sample handling was carried out in a glove box under purified argon atmosphere (less than 1 ppm O_2 and H_2O). Consolidation was carried out by uniaxial hot pressing and hot extrusion under argon atmosphere at 513K and 700 MPa. The phases and the microstructure were characterized by X-ray diffraction (XRD) (Cu K_α radiation). The thermal stability of the samples was investigated by differential scanning calorimetry (DSC) at 40 K/min heating rate under a continuous flow of purified argon.

3. RESULTS AND DISCUSSION

In contrast to rapid quenching, no complete amorphization is generally achieved by MA for Al contents larger than 80 at.% [4], but the powders consist of an amorphous phase/fcc Al phase mixtures, most likely coexisting with some intermetallic compounds. However, for $A_{85}Y_8Ni_5Co_2$ complete amorphization can be achieved by using proper milling conditions, i.e. interval-milling at low intensity corresponding to a rather low kinetic energy and resulting in a low milling temperature [5]. The complete amorphization of multi-component Al-rich alloys by MA, combined with proper annealing, promises a further extension of the mechanical attrition technique for the preparation of Al-rich multiphase nanostructured materials. The quasicrystalline or glassy powders can then be consolidated into nearly full density bulk specimens by extrusion or hot-pressing at temperatures below the decomposition temperature of the nanoscale quasicrystals [5]. A typical example is gas-atomized and extruded Al-Cr-Cu-Mn powder [6], which displays a rather high strength of about 600 MPa and a good ductility exceeding 15%.

Alternatively to mechanical alloying of elemental powder mixtures, Al-based glassy powders can be produced by controlled milling of melt-spun glassy ribbons. For example glassy powders have been obtained from $Al_{85}Ni_9Nd_4Co_2$ glassy ribbons after ball milling for 9 hours [7]. For pulverizing the melt-spun ribbons, cryogenic milling was used in order to overcome the very high ductility of the ribbons and to retain their glassy structure. The milling was performed as a sequence of 15 minutes milling intervals interrupted by 15 minutes breaks to avoid a strong temperature rise and to suppress recovery processes in the low melting metal aluminum. Due to the controlled milling conditions, the ball milled ribbons display a strikingly similar structure and crystallization behavior compared to the parent as-spun sample [7]. The glassy powders were then consolidated through two different processes: uniaxial hot pressing and hot extrusion.

Fig. 1 compares the XRD patterns for the bulk samples consolidated by uniaxial hot pressing and hot extrusion and the as-milled powder. For the hot-pressed sample, the broad diffuse maximum and a shoulder indicate that the compact has quite similar structure to the milled powders. However, there is about 6% volume fraction of voids in the hot-pressed compact. In contrast, the extruded sample is a composite with nanostructured α-Al solid solution embedded in an amorphous matrix (the Cu phase peaks stem from the Cu can used for encapsulation of the samples). This kind of amorphous-nanocrystalline composite may have excellent mechanical properties combining high strength and high ductility [8]. At the same time, the extruded compact has higher density due to smaller residual porosity (< 2%) in the sample compared with the

Table 1. A summary of the mechanical properties from the compression tests of the Al-30 wt.% $Ni_{60}Nb_{40}$ MMCs prepared by sintering, hot-pressing and hot-extrusion at 823K.

	Furnace sintering	Hot-pressing	Hot-extrusion
Young's modulus *E* (GPa)	65.2	67.3	72.2
Yield strength $\sigma_{0.02}$ (MPa)	94	106	134

hot-pressed specimens (~6%). Although the extrusion temperature (513K) is low enough to avoid the time-dependent precipitation of α-Al as the first crystallization product, about 24% volume fraction of nanostructured α-Al solid solution precipitates during extrusion (evaluated from DSC and XRD data).

Although it is improper to test compressive mechanical properties due to the presence of up to about 6% voids in the compacts, the mechanical properties evaluated by microhardness measurements are promising. Vickers microhardness tests give values of about 382 H_v for the as-spun ribbon prepared at 21 m/s, 380 H_v for the hot-pressed sample and 350 H_v for the extruded sample. The difference of hardness observed between hot-pressed and extruded specimens most likely arises from the different microstructures characterizing the differently prepared samples. These values are much higher than those (100~190 H_v) of conventional high-strength crystalline Al-based alloys and are comparable with those (340 H_v) reported for melt-spun amorphous $Al_{85}Ni_5Y_8Co_2$ [9]. A rough estimate of potential ultimate strengths according to the empirical equation promises ultimate strengths of about 1310 MPa, which is similar to other Al-TM-RE glassy alloys.

A different approach to obtain high-strength materials consists of using a metallic glass as reinforcement in metal matrix composites (MMCs) through infiltration casting or sintering techniques. The crystallization temperature of metallic glasses used as reinforcement in MMCs is of primary importance for consolidation via sintering methods. In order to prevent the glass from crystallization, the highest temperature used for sintering should be lower than the crystallization temperature of the glass reinforcement. In order to avoid crystallization, a metallic glass reinforcement with a crystallization temperature higher than the melting temperature of the metal matrix may be selected [10]. However, most of the currently available metallic glasses exhibit crystallization temperatures that are lower than the melting temperatures of Al and Mg, two of the most used matrix materials for MMCs [11].

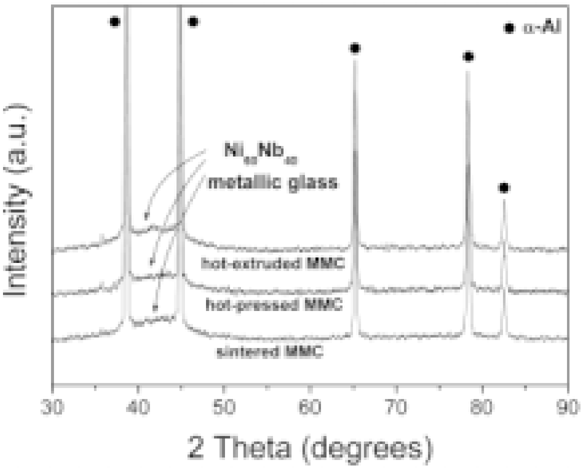

Fig. 2. XRD patterns of the Al-30 wt.% $Ni_{60}Nb_{40}$ MMCs prepared by sintering, hot-pressing and hot-extrusion at 823 K.

A different strategy is to develop some techniques by which the metallic glass-reinforced matrix composites are produced at temperatures below the melting temperature of the matrix [12]. For example, Al-30 wt.% $Ni_{60}Nb_{40}$ metallic glass particle-reinforced MMCs have been produced by sintering, hot-pressing and hot-extrusion at a relatively low temperature. $Ni_{60}Nb_{40}$ glassy powders were firstly produced by mechanical alloying and subsequently combined with pure Al as matrix. In order to prevent the $Ni_{60}Nb_{40}$ from crystallization, the fabrication temperatures for all the three samples are set to be 823K, which is 50K lower than the temperature at which crystallization peaks start to occur in the DSC isotherms. Fig. 2 shows the XRD patterns for the three samples prepared by different routes, all of them exhibit the sharp peaks of Al on the top of the maxima representing the amorphous $Ni_{60}Nb_{40}$ reinforcement, which indicates that the $Ni_{60}Nb_{40}$ reinforcement survives the high temperature during sample preparation.

The $Ni_{60}Nb_{40}$ glass was chosen because it displays a rather high crystallization temperature (however lower than the melting temperature of Al) [12] and, therefore, it is quite stable during the sintering process. In addition, Ni-Nb-based glassy alloys are characterized by strength higher than 2000 MPa and Vickers hardness of about 800 [13]. Thus they are suitable as reinforcement in Al-based MMCs. The results from the compression tests for the three samples prepared by different method are summarized in Table 1. The Young's moduli for the sintered, hot-pressed and hot-extruded samples are 65.2, 67.3, and 72.2 GPa, while their yield strengths are 94, 106 and 134 MPa, respectively. These results indicate that the high pressure used in hot-pressing and hot-extrusion helps to increase the mechanical properties of the Al-30 wt.% $Ni_{60}Nb_{40}$ MMCs.

4. SUMMARY

Results on the formation and mechanical properties of Al-based mechanically attrited powders containing amorphous or nanocrystalline phases, Al-based MMCs containing metallic glass reinforcement and their consolidation into bulk specimens have been reported. This class of materials not only offers a new scope for applications due to the promising mechanical properties (very high room temperature strength together with good ductility) but also provides the possibility of discovering and developing new materials with interesting properties.

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