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MECHANICAL PROPERTIES OF MG ALLOYS AMX602 AND AZXE7111 UNDER QUASI-STATIC AND DYNAMIC LOADING

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Abstract

Mg and its alloys have drawn great interest in the materials community due to their high specific strength and potential applications in industry. In this work, we present some experimental results on two Mg-alloys, AMX602 and AZXE7111. We have evaluated the dependence of the mechanical properties of these alloys on the extrusion temperatures under both quasi-static (strain rate $\sim 1\times10^{-3}$ s^{-1}) and dynamic (strain rate $\sim 4\times10^{3}$ s^{-1}) uniaxial compressive loadings. We have observed that the quasi-static yield strength of AMX602 exhibits a slight dependence on the extrusion temperature, whereas the ultimate strength and the deformation-to-failure do not show such dependence. On the other hand, the dependence of the mechanical properties of AZXE7111 is much more complicated. We have also found that the deformation-to-failure of both alloys increases at increased strain rate. For comparison, we have tested two conventional Mg-alloys, WE43 and AZ91C under very similar conditions. We have found that AMX602 and AZXE7111 show significantly improved mechanical properties compared to WE43 and AZ91C under either quasi-static or dynamic loading. Such knowledge is particularly important for applications involving impact loading.

Introduction

Magnesium is one of the lightest metals of practical interest in many application areas [1, 2]. Magnesium-based alloys have been used, and are showing prominently strong potential as candidates in applications such as automotive, railway, electronic packaging and especially aerospace in light of their extraordinarily low specific weight. In the past few decades, alloy design and fabrication has been an arena of intensive attention in the materials science and engineering community. Among the drawbacks associated with Mg-alloys are their limited tensile ductility (due to the lack of five independent slip systems in single crystal Mg), their relatively poor corrosion resistance, and their anisotropy in mechanical properties. The limited tensile ductility which entails undesirable workability of Mg-alloys has particularly become one of the stumbling blocks for their wide application.

In view of this, in the past dozens of years, a great amount of efforts have been exercised to improve the mechanical properties of pure Mg and Mg-alloys, primarily through the various ways of refining the grain size and modifying the texture [3-5]. For instance, a number of effective approaches have been used in obtaining ultrafine-grain (UFG, grain size d within 100 nm < d ≤ 1000 nm) or nanocrystalline (NC, d<100 nm) microstructures. Techniques involved in achieving such microstructures include electro-deposition [6], powder metallurgy [7], and severe plastic deformation (SPD) [8]. In recent years, SPD methods have been widely used in producing UFG/NC microstructures in Mg-alloys as well as in other metals and alloys such as copper, nickel, steels, tungsten, iron, niobium and tantalum [9-11]. Equal-channel angular extrusion (ECAE) has attracted special interest in this respect, which was also employed to modify the texture of Mg and its alloys [3, 5, 12].

In the past, a great deal of research efforts as evidenced by the large volume of literature has been focused in part on modifying the microstructures of traditional AZ-series Mg-alloys by SPD processes [13-15]. This is based on the observation that although as-cast Mg/Mg-alloys exhibit brittle behavior at ambient temperature, the ductility can be improved by subjecting the ingots to SPD at moderate temperatures. Mukai and co-workers [16] explained that the enhanced ductility is because of the redistribution of basal planes (0001) within the alloy during the SPD process. However, the increase in ductility is at the cost of the yield stress. By using X-ray diffraction (XRD), Feng et al. [17] confirmed that the strong texture initially observed in the as-extruded Mg alloy can be mitigated by ECAE processing. Agnew and co-workers [5] reported a strong orientation effect in eight-path ECAE processed AZ31B and argued that the orientation and its distribution are much more important than any other effects such as the Hall-Petch relationship in determining the yield strengths of the Mg alloys with hexagonal close packed (HCP) structure. Kim et al. [13] also observed ductility improvement and some loss in the yield strength of AZ61 after ECAE. They explained that the change in texture has contributed to the overall change in mechanical behavior.

Besides grain refinement and texture modification, a few researchers have also paid attention to alternative approaches in order to improve the mechanical properties of Mg-alloys, such as Mg-based metal matrix composites [18, 19]. Among such efforts, we have recently developed some new Mg-alloys based on certain concepts of alloy design and fabrication. In particular, in the present work, we will describe some mechanical testing results on two newly developed Mg-alloys, AMX602 and AZXE7111. Fine powders of these alloys were produced by the spinning water atomization process (SWAP), followed by compaction and extrusion at different temperatures. Details of alloy design and production have been described elsewhere [20-22]. Elsayed et al. [23], reported that the newly developed Mg-alloys show great improvement in quasi-static tensile properties against conventional cast ones that are extruded in the same way as the SWAP ones. They have also investigated the microstructure of these newly developed alloys including grain size, crystal orientations and second-phase particles [20-23]. In the present work, we have investigated the mechanical properties of these two Mg-alloys under uniaxial compressive quasi-static and dynamic loading. These alloys were prepared by the spinning water atomization process (SWAP), in which gas atomization is combined with water atomization to produce very high solidification rates (of about 10^6 K/s), resulting in fine microstructures and super-saturation of alloying elements, and then followed by cold compaction at room temperature with a pressure of 600 MPa. They were finally extruded at temperatures of 573~673 K at an extrusion ratio of about 37 [22]. For the purpose of comparison, we have also examined the traditional Mg-alloys WE43 and AZ91C.

Experimental

Materials and Mechanical Testing Samples

In the present study, Mg-alloys of AMX602 (Mg-6%Al-0.5%Mn-2%Ca, all in weight percentage) and AZXE7111 (Mg-7%Al-1%Zn-1%Ca-1%La, all in weight percentage) have been investigated. Both alloys were fabricated at the Joining and Welding Research Institute, Osaka University, Japan. Briefly, spinning water atomization (SWA) technique was used in producing the powders of the alloys with desired chemical composition. The powders were then collected, compacted and consolidated by extrusion at various temperatures. The details of the alloy production have been provided by Kondoh and co-workers elsewhere [20]. Three different rods of each alloy (from which the samples were machined) were extruded at three different temperatures. Specifically, for AMX602 the extrusion temperatures are 350 °C, 300 °C and 250 °C, and for AZXE7111 the extrusion temperatures are 350 °C, 250 °C and 200 °C. Samples were cut from these rods, both in the flow (extrusion) direction and in the transverse direction. Quasi-static compression samples have a rectangular geometry with square loading faces and a height/width ratio of 2:1, following the ASTM standard for such experiments. High-strain rate uniaxial compression samples have cuboid shape, which is also commonly used and well characterized in the community [24, 25]. For comparison, as-cast Mg-alloy WE43 and as-extruded Mg-alloy AZ91C, supplied by commercial venders, were also tested under both quasi-static and dynamic conditions. More specifically, the dimensions of the specimens for uniaxial quasi-static compressive tests is 2.5 mm × 2.5 mm × 5.0 mm (5.0 mm is the gauge length), while the geometry for uniaxial dynamic compressive tests is 2.5 mm × 2.5 mm × 2.0 mm (2.0 mm is the gauge length).

Quasi-static and High Strain-Rate Mechanical Testing Experiments

The loading faces of all specimens were polished with diamond paper down to 3 μm. The mechanical testing at quasi-static strain rate (strain rate $\sim 1\times10^{-3}$ s^{-1}) was performed by using an MTS hydraulic universal testing machine with self-alignment features. Lubricant (grease) was applied between the compression platens and the loading faces of the specimens to reduce or eliminate frictional effect. The prescribed desirable strain rate was achieved by controlling the velocity of the loading actuator (the speed of the cross-head).

We used a Split Hopkinson Pressure Bar (SHPB, or Kolsky bar) system to perform high strain rate (strain rate $\sim 1\times10^{3}$ s^{-1}) uniaxial compression. Details of such a system, its working principle, data processing and caveats can be found in several handbook articles [24, 26] and the monographs [25, 27]. Briefly, in this experiment, the specimen that has the required dimension is sandwiched between two co-axial elastic bars of the same diameter made of very high-strength maraging steel (usually called the input/out, or incident/transmitter bars). During the experiment, a projectile (or bullet) made of the same steel with the same diameter is launched by the pressurized gas released from a gas tank and strikes one end of the input bar. The impact generates a stress wave which travels down the input bar and reaches the input bar/specimen interface. Part of the stress wave is reflected back into the input bar, and part of it is transferred into the specimen and then to the output bar. Strain gages are attached to the surfaces of the input/output bars, the signals of which are recorded by a multiple channel high-speed oscilloscope. The data can then be processed to result in the high strain-rate stress-strain curve of the specimen. In this study, due to the limited dimensions of the specimens, we use a desk-top Kolsky bar (DTKB) to evaluate the high strain-rate stress-strain behavior of the specimens. The diameter of the various bars is 4.975 mm. We used a pulse shaper made of a thin copper disk at the impact end of input bar to modify the input stress wave. The interfaces between the specimen and the input/output bars were also lubricated to mitigate frictional effects. At least three samples were tested for each condition to get an indication of reproducibility.

For the dynamic experiments, the data were all collected as a function of time. They were then converted into true stress-strain curves. The incident pulse signal $\varepsilon_i(t)$, reflected pulse signal $\varepsilon_r(t)$, and transmitted pulse signal $\varepsilon_t(t)$ were processed to calculate the strain and stress data based on one-dimensional wave theory [28].

Results and Discussion

Figure 1 shows the mechanical properties (strength) under uniaxial compression in dependence on the extrusion temperature for AMX602 (a) and AZXE7111 (b). In these plots, "Flow" designates that the loading direction is in the flow or extrusion direction of the material, while "Trans" means that the loading is in the transverse direction of the material. QS and DY indicate quasi-static and dynamic loading, respectively. YS and US are for yield strength and ultimate (maximum) stress, respectively. The stress quantity is the true stress.

We can see that when the extrusion temperature increases, the strength (both yield and ultimate) of both AMX602 and AZXE7111 decreases. This trend holds true at both quasi-static strain rate (1×10^{-3} s^{-1}) and high strain rate (4×10^{3} s^{-1}). We can also notice that, when tested in the flow direction, the specimen generally exhibits slightly higher strength levels than when tested in the transverse direction. It points to some minor anisotropy of the mechanical properties in both Mg-alloys. However, compared to conventional extruded Mg-alloys, the anisotropy is much alleviated. Another point of interest based on the data points in Figure 1 is that, for the same alloy under the same loading condition (either quasi-static or dynamic) the ultimate strength is much higher than the yield strength. This suggests that both alloys have strong strain hardening under uniaxial compression.

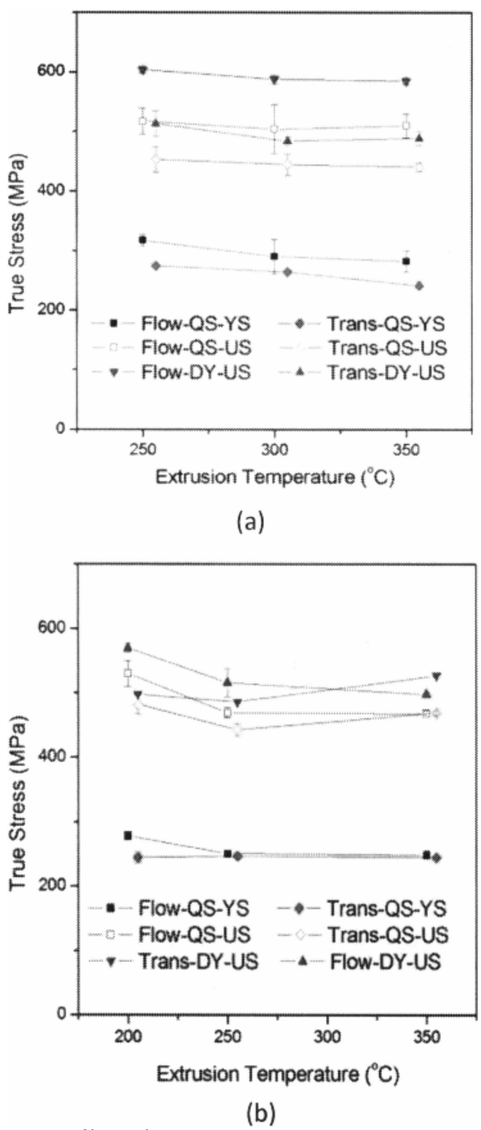

Figure 1. Effect of extrusion temperature on the quasi-static and dynamic compressive strengths of AMX602 (a) and AZXE7111 (b) Mg-alloys. The legends within the plots have the same meaning: "Flow" means that the specimen was loaded in the flow (or extrusion) direction; "Trans" means that the specimen was loaded in the transverse direction; QS and DY indicate quasi-static and dynamic loading, respectively; YS and US suggest the data are for yield strength and ultimate strength, respectively.

In Figure 2 we have plotted the deformation to failure or the total compressive strain as a function of extrusion temperature for AMX602 (a) and AZXE7111 (b). The strain values are the true strain. We should point out that most of the specimens did fail upon either quasi-static loading or dynamic loading. Therefore, in the case where the specimen did not fail, the data point corresponds to the total (prescribed) strain. Figure 2 provides some information associated with the ductility or malleability of the two Mg-alloys. Figure 2 (a) suggests that the ductility of AMX602 alloy does not depend very much on the direction of loading; that is, it is more or less plastically isotropic regardless of the extrusion temperature. Also clear from this plot is that the extrusion temperature only has a marginal effect on the deformation to failure of AMX602. This is nearly true also for AZXE7111.

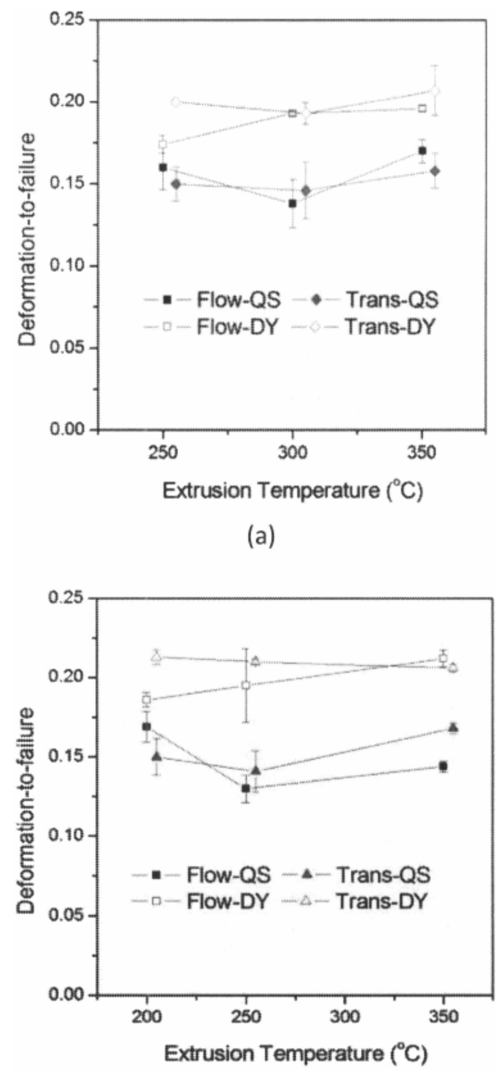

Figure 2. Total true compressive strain, or deformation-to-failure of AMX602 (a) and AZXE7111 (b) as a function of extrusion temperature. The meaning of the legend in the plots is the same as that of Figure 1.

Such observations indicate that during warm extrusion, the change in extrusion temperature only has some marginal effect on the microstructural evolution of the alloy. Or we may postulate that dynamic recrystallization dominates during extrusion and grain growth might have been limited due to lack of time. In other words, the chemical composition design of the alloy has effectively resulted in an extrusion temperature insensitive Mg-alloy. The same conclusion applies to AZXE7111 as indicated by Figure 2 (b).

Our experimental results show that either in quasi-static or dynamic loading, AZXE7111 is less anisotropic than AMX602 in terms of the differences of yield stress and ultimate compressive stress between flow direction and transverse direction. This observation is in line with the results reported by Elsayed et al. [22]. Elsayed and co-workers tried to explain the results on the basis of the more random distribution of crystal orientations induced by the effect of rare-earth addition in AZXE7111 alloy.

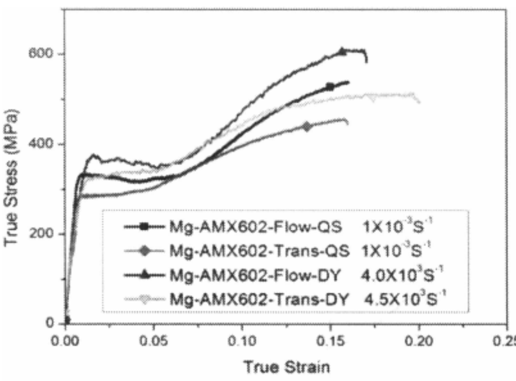

Figure 3. True stress vs. true strain curves of AMX602 at low and high strain rates.

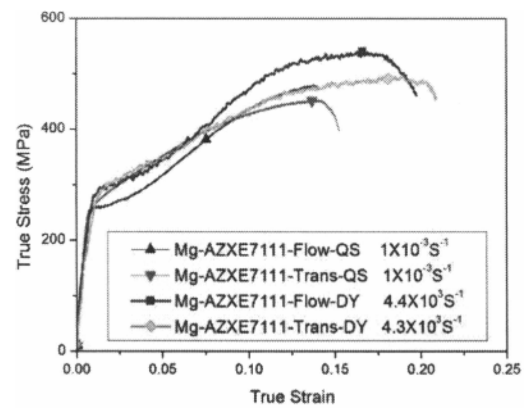

Figure 4. True stress vs. true strain curves of AZXE7111 at low and high strain rates.

As we have noticed, large differences between yield stress and ultimate stress are observed for both AMX602 and AZXE7111, which indicates that strong strain hardening has taken place in the materials in the process of mechanical loading. Actually, alloy AMX602 shows extensive nearly perfect plasticity immediately after yielding, lasting for a large range of plastic strain, and then followed by significant strain hardening. The micro-mechanism of such behavior of plasticity could be initial easy basal slip followed by more difficult prismatic, pyramidal slip, or even mechanical twinning. All these mechanisms of plastic deformation have been reported in Mg and its alloys. Particularly the sharp increase in strain hardening is associated with the operation of mechanically harder slip systems or twinning processes. As shown in Figure 3 and Figure 4, the nearly perfect plasticity was not found in AZXE7111, but rather almost steady strain hardening after yielding until failure or discontinuation of the loading process. This is in sharp contrast to the behavior of alloy AMX602. This difference may be explained by the presence of the rare earth La atoms and the larger amount of other alloying elements in AZXE7111 than in AMX602, which elements and the corresponding compound particles have been well recognized by Elsayed et al. [21]. Additionally, preliminary transmission electron microscopy (TEM) and Energy Dispersive Spectroscopy (EDS) (not shown in this article) have asserted this presumption. As a result, more second-phase particles such as Al-Ca and Al-La are present in the alloy that renders basal slip more difficult. The alloy starts to have plastic deformation by directly appealing to mechanically more difficult plastic deformation mechanisms such as prismatic, pyramidal slip or even deformation twinning.

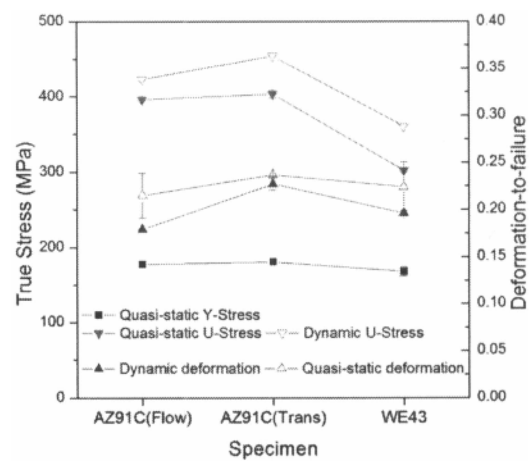

Figure 5. Total compressive strain or deformation-to-failure of AZ91C and WE43. Y and U indicate yielding and ultimate, respectively.

For comparison, conventional Mg alloys AZ91C and WE43 were also tested in the same conditions as those for the newly developed alloys. Figure 5 shows the strength (the yield stress and ultimate stress) and deformation-to-failure of these two conventional Mg alloys. Both flow and transverse directions of AZ91C exhibit no more than 200 MPa of yield stress and around 400 MPa of ultimate stress. In contrast, the newly developed alloys exhibit yield stresses and ultimate stresses around 300 MPa and 500 MPa, respectively. Meanwhile, WE43 is not even comparable with AZ91C as shown in the results, not to mention the new alloys. Though the deformation-to-failure of the conventional alloys shows a little bit higher values than those of the new alloys, the overall performance of AMX602 and AZXE7111 still outplays the conventional alloys.

Conclusions

We have examined the quasi-static and dynamic uniaxial mechanical properties of two new Mg-alloys AMX602 and AZXE7111. The latter has La as alloying element. Both alloys were produced by spinning water atomization followed by compaction and extrusion at various temperatures. The quasi-static and high strain-rate mechanical testing (uni-axial compression) were performed on these two alloys in both the extrusion (flow) and transverse directions. The results show that both alloys exhibit marginal anisotropic behavior, both in terms of mechanical strength and plasticity under compression. The strength in the extrusion direction is slightly higher than in the transverse direction. Difference in compressive plasticity between the two directions is yet quite small. Both alloys show significant strain hardening. AMX602 exhibits extensive nearly perfect plasticity after yielding followed by strain hardening, while AZXE7111 displays strong strain hardening immediately after yielding. We attribute this difference to the presence of La in AZXE7111 which facilitates precipitation hardening.

Acknowledgements

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