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Viewpoint Paper

Current issues in magnesium sheet alloys: Where do we go from here?

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Critical issues relating to the strength and formability of Mg sheet alloys are assessed. It is shown that Mg alloys in general have slow aging kinetics and even the most formable Mg alloys have less than optimum orthotropic texture. It is suggested that future research and development efforts should be concentrated on identifying the alloying elements and optimizing the related processes that can accelerate the age-hardening response and modify the texture to be weak and symmetric in the sheet plane.

Keywords: Magnesium alloys; Strength; Precipitation; Texture; Formability

The world currently faces significant challenges in energy conservation and environmental protection. Among various end-use energy sectors, the transportation sector is the second in energy consumption and the first in energy-related CO_2 emissions [1,2]. One of the most effective ways to overcome such problems associated with transportation systems is the use of lightweight alloys, e.g. Mg alloys, as structural components of vehicles. Lightweight alloys are also important for improving the efficiency of hybrid-type vehicles because they offset the additional weight of batteries and electric motors. Recent studies have shown that some extruded Mg alloys have good mechanical properties comparable to those of competing materials such as Al alloys (e.g. [3,4]). On the other hand, there is a lack of competitive Mg alloy sheet products, which are much needed for numerous weight-sensitive applications.

There are several fundamental and technical issues that need to be overcome in order to develop high-performance Mg alloy sheets. For example, Mg alloys usually develop strong basal texture during rolling, resulting in anisotropic mechanical properties and poor formability. Although additions of rare earth (RE) elements are known to randomize the texture [5–8], resulting in an improvement in the formability of Mg alloys at room temperature to some extent [9–12], new alloy design concepts need to be developed to randomize the texture using cheaper alternative elements. Another problem is the rather sluggish precipitation response of Mg alloys [13], which needs to be enhanced in order to develop high-strength Mg alloys comparable in strength to Al alloys. It is necessary to find an alloying element or combination of elements that can improve the age-hardening response of Mg alloys. For the practical application of Mg alloy sheets, a more immediate issue than the properties is the high cost of sheet products, resulting from, among other things, the repetitive reheating and rolling steps required to produce them. Recently, application of twin-roll casting technology has been shown to be capable of producing high-quality Mg alloy sheets cost effectively, reducing the number of hot rolling steps [14–16]. However, dependence on RE elements in some alloys and lack of formability at room temperature add to the cost of the final products. Although Mg alloys usually show quite acceptable formability at high temperatures [17,18], high-temperature

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forming of Mg alloys is inefficient and energy intensive, making the Mg alloy sheets unattractive for automotive applications. It should also be noted that high-temperature forming of age-hardened or strain-hardened alloys creates materials that are susceptible to softening after forming due to dissolution/coarsening of strengthening precipitates or recovery/recrystallization, respectively. Therefore, to make Mg alloys commercially viable, the formability of Mg alloys at room temperature should be improved, without utilizing RE elements, to a level at least similar to those of Al alloys.

The aim of the present paper is to critically assess the ongoing research and development efforts on the mechanical properties of Mg sheet alloys and suggest future research areas needed to develop commercially viable Mg alloy sheets.

2. Mechanical properties of magnesium sheet alloys

2.1. Tensile properties

Figure 1 shows the tensile properties of representative Mg alloy sheets [8–12,16,19–36]. Some of these have tensile properties equivalent to those of low to medium strength 5XXX and 6XXX Al alloys. It shows that even AZ31 alloy can have yield strength higher than 400 MPa with reasonable ductility, when processed by severe plastic deformation [23].

Unlike the case of texture modification, additions of RE elements are not necessarily required to obtain high strength in Mg alloys. In fact, most of RE-containing Mg alloys have low strength in the range of 150–200 MPa, mainly due to a weakened basal texture. Exceptions are the ones using fairly large amounts of RE elements, e.g. alloys having long period stacking ordered structure [32,33,37] and an alloy strengthened by nanospaced stacking faults [36]. In comparison, precipitation-strengthened Mg–Zn-based alloys can provide yield strength >300 MPa [16,26,27]. Considering that strong basal texture is responsible for poor formability at low temperatures, utilization of a strong basal texture for strengthening Mg alloys is not desirable and other strengthening mechanisms, particularly precipitation strengthening, should be utilized to realize high strength in Mg alloys.

Several important guidelines for precipitation strengthening in Mg alloys have been suggested by Nie [13] and Hono et al. [38]. Besides the characteristics of precipitates, i.e. structure, morphology and orientation, required for achieving high strength in Mg alloys discussed by Nie [13] and Hono et al. [38], another critical issue related to precipitation strengthening in Mg alloys is their very slow age-hardening response. For example, it would take about 120 h at 160 °C to reach peak hardness for Z6 alloy, which is one of the typical age-hardenable Mg alloys [39]. This is also true for RE-containing alloys [40], which have a great potential for age hardening. Such very slow aging kinetics of RE-containing alloys might originate from the very slow diffusivities of the RE elements.

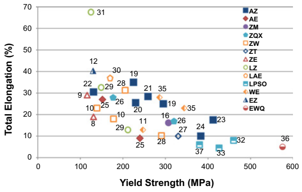

Figure 1. Room-temperature longitudinal yield strength and total elongation of representative Mg sheet alloys. The number adjacent to the data point denotes the reference number.

The need for accelerated aging kinetics for Mg alloys mainly comes from a need to reduce the cost associated with the fabrication of Mg alloy sheets into final products. Although only limited data exists on the low-temperature formability of high-strength (yield strength >300 MPa) Mg alloys [41], it is expected that the already poor formability of Mg alloys will be degraded even further as the alloy strength increases. Therefore, to be competitive with Al alloys and low-C steels, Mg alloys should be capable of being age hardened within a short period of time after forming, such as experienced during the bake-hardening process utilized for fabricating steel parts for automotive applications.

For the alloys to have an accelerated aging kinetics, the alloying elements should have the following characteristics: (i) a large difference in the solubilities between the solution treatment and aging temperatures; and (ii) a high diffusivity at the aging temperature [42]. Although there are several alloying elements which possess the first characteristic, e.g. Sn and RE elements, their diffusivities are usually very slow (e.g. 10^{-11} cm s^{-2} for Sn vs. 2.1×10^{-10} cm s^{-2} for Zn at 400 °C). These alloying elements are more suitable for creep-resistant Mg alloys, which require thermal stability of the second phases [43]. Therefore, some other novel approaches should be taken to accelerate the aging kinetics of Mg alloys.

Previous studies on Mg and Al alloys have shown that at least two approaches are possible for accelerating the aging kinetics of Mg alloys: (i) utilization of dispersoids acting as nucleation sites for precipitation [16,44]; and (ii) deformation prior to aging [45]. In addition, it has been shown that the aging kinetics of Mg–8Zn alloys can be significantly accelerated by the addition of alloying elements such as Co [46] and Ba [47], which can increase the possible solution treatment temperature without the occurrence of incipient melting, resulting in increases in the numbers of supersaturated Zn atoms and vacancies in the Mg matrix after solution treatment.

The aging kinetics of Mg alloys can also be accelerated by co-segregation and/or co-precipitation of solutes induced by microalloying additions. For example, it has been shown that additions of In significantly accelerate the aging kinetics of Mg–0.3Ca (at.%) alloy systems [48]. It has been shown that the precipitates are enriched with Ca and In, which has been suggested to be due to a large negative enthalpy of mixing between Ca and In (~35 kJ mol^{-1}) compared with those for Mg–Ca (~6 kJ mol^{-1}) and Mg–In (~4 kJ mol^{-1}). Similar behavior has been found recently in Na-added Mg–10Sn–3Al–1Zn alloy, showing co-segregation of Na with Sn [49]. On the other hand, the accelerated aging kinetics of Zn-added Mg–Ca alloy [50] and Mg–Gd alloy [51] is suggested to be due to the co-segregation of solutes having a large atomic size difference. When