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Effect of eutectic temperature on the extrudability of magnesium–aluminum alloys

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The limited extrudability of AZ31 (Mg–3Al–1Zn) alloy is reported to be caused by incipient melting of the $Mg_{17}Al_{12}$ binary phase with a eutectic temperature of 438 °C. Computational phase equilibria and microstructural examination, however, show that Mg–Al–Zn ternary phases with eutectic temperatures as low as 338 °C are actually present in the AZ31 alloy, which is indeed the real limitation to its extrudability. The significantly improved extrudability of AM30 alloy (Mg–3Al–0.3Mn) is due to the absence of these zinc-containing eutectic phases.

Keywords: Magnesium alloys; Extrusion; Eutectic solidification; Microstructure; Mechanical properties

AZ31 (Mg–3%Al–1%Zn (all compositions are in wt.% except otherwise stated)) alloy is the most popular magnesium extrusion alloy. However, this alloy has a much lower maximum extrusion speeds than Al–Mg–Si-based 6xxx series aluminum alloys, resulting in higher manufacturing costs compared to aluminum extrusions [1]. For Mg–Al–Zn (AZ)-type alloys, the low melting point of 438 °C of $Mg_{17}Al_{12}$ phase was reported to cause hot-shortness during extrusion and thus poor extrudability [2]. Magnesium alloys also have less formability compared with steel and aluminum at room temperature. The limited extrudability and formability of magnesium extrusions has been a major technical barrier for their application in automotive components.

AM30 (Mg–3%Al–0.3%Mn) is a new extrusion alloy developed to provide improved extrudability and formability compared with conventional AZ31 alloy [3,4]. This research investigates the phase equilibria of the AZ31 and AM30 alloys using computational thermodynamics calculations and experimental validation to provide a metallurgical understanding of extrudability, which will help us to optimize the extrusion and forming processes of these alloys for structural applications.

The experimental alloy AM30 and the commercial alloy AZ31 were used to extrude tubes of a nominal outside diameter of 70 mm and a nominal thickness of 4 mm. For each alloy, about 900 kg of melt was prepared and cast into billets 178 mm diameter and 406 mm long, using a direct-chill caster. The chemical composition of the two alloys, shown in Table 1, is within their specification limits. Billets of both alloys were heated to desired extrusion temperatures of 320, 360 and 400 °C, and tubes were extruded at various extrusion (ram) speeds from 1 to 10 mm s^{-1} in a 1400 ton press at Timminco, Aurora, CO.

The microstructure of the alloy tube specimens was analyzed with a Zeiss EVO-50 scanning electron microscope (SEM; Carl Zeiss SMT AG, Oberkochen, Germany) equipped with a Thermo Noran energy dispersion system (EDS; Thermo Electron Corporation, Waltham, MA). For SEM analyzes, secondary electron images were taken at an accelerating voltage of 10 keV, and EDS analyzes were performed in selected areas at an accelerating voltage of 20 keV.

The thermodynamic calculations of the Mg–Al–Zn alloy system were carried out using the software package Pandat (developed by CompuTherm, Madison, WI [5]), coupled with the latest thermodynamic database Pan Mg (compiled by the Clausthal University of Technology, Clausthal-Zellerfeld, Germany [6]). Figure 1a shows the calculated liquidus projection of the Mg–Al–Zn system in the Mg-rich corner using the Scheil model, which is based on the assumption of complete mixing in the liquid but no diffusion in the solid. Generally, the liquidus temperature decreases with the addition of Al (up to at least about 30%) and Zn (up to at least about 50%). This

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Table 1. Chemical composition of AZ31 and AM30 alloys (in wt.%).

Alloy	Al	Mn	Zn	Fe	Ni	Cu
AZ31	3.2	0.34	1.05	0.0025	0.0007	0.0008
AM30	3.4	0.33	0.06	0.0026	0.0006	0.0008

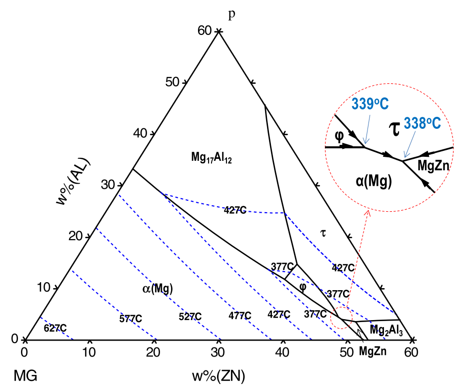

Figure 1a. Calculated liquidus projection of the Mg–Al–Zn alloy system.

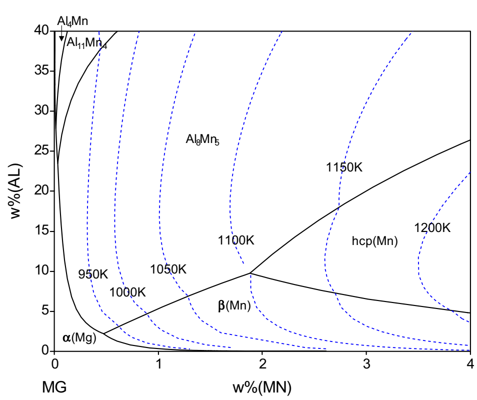

Figure 1b. Calculated liquidus projection of the Mg–Al–Mn alloy system.

ternary phase diagram shows two Mg–Al–Zn based @ternary phases, φ and τ, in the Mg-rich region. The τ phase with cubic crystal structure (space group *Im*$\bar{3}$) [7] was described by the compound energy formalism (CEF) as $(Mg)_{26}(Mg,Al)_6(Al,Zn,Mg)_{48}(Al)_1$ [8]. The φ phase has an orthorhombic structure (space group *Pbc*2$_1$ *or Pbcm*) [9], and is described by the two-sub lattice formula $Mg_6(Al,Zn)_5$ according to its crystal structure and homogeneity [8]. As shown in the enlarged circle in Figure 1, the two ternary phases form via the following two transformations within a very narrow low temperature region:

(1) type II invariant reaction at 339 °C, $L + \varphi \rightarrow \alpha(Mg) + \tau$; and
(2) ternary eutectic reaction at 338 °C, $L \rightarrow \alpha(Mg) + \tau + MgZn$.

Figure 1b is an enlarged section of the Mg-rich corner of the calculated liquidus projection of the Mg–Al–Mn system. While the calculated phase diagram, based on the Scheil model, shows a series of Al–Mn compounds during solidification of Mg–Al alloys with a minor Mn content (1–4%), only the Al_8Mn_5 phase was confirmed in the as-cast microstructure in Mg-rich Mg–Al–Mn-based alloys [10–12]. The calculated fractions of Al_8Mn_5, $Al_{11}Mn_4$ and Al_4Mn phases in AM30 are 1.1%, 0.002% and 0.001%, respectively. Therefore, it is reasonable to conclude that Al_8Mn_5 is the only significant Al–Mn binary phase in the AM30 solidification microstructure.

Similarly, commercial AZ alloys such as AZ31 contain about 0.3% Mn. It is important to understand the solidification path of these alloys in the quaternary Mg–Al–Zn–Mn system. Figure 2 shows the solidification curve (temperature vs. solid fraction) of AZ31 alloy based on the Scheil simulation of the ternary system, compared with that of AM30 alloy based on the Mg–Al–Mn system calculation. The solidification path for the AZ31 alloy is listed as follows:

(1) nucleation of primary Mg (starting at 631 °C): $L \rightarrow \alpha$ (Mg);
(2) formation of Al_8Mn_5 (starting at 629 °C): $L \rightarrow \alpha$ (Mg) + Al_8Mn_5;
(3) binary eutectic reaction (starting at 412 °C): $L \rightarrow \alpha$ (Mg) + $Mg_{17}Al_{12}$;
(4) binary eutectic reaction (starting at 366 °C): $L \rightarrow \alpha$ (Mg) + φ;
(5) type II invariant reaction (339 °C): $L + \varphi \rightarrow \alpha(Mg) + \tau$; and
(6) ternary eutectic reaction (338 °C): $L \rightarrow \alpha(Mg) + \tau + MgZn$.

In the absence of Zn, however, the AM30 alloy assumes a simplified solidification path:

(1) nucleation of primary Mg (starting at 634 °C): $L \rightarrow \alpha$ (Mg);
(2) formation of Al_8Mn_5 (starting at 632 °C): $L \rightarrow \alpha$ (Mg) + Al_8Mn_5; and
(3) binary eutectic reaction (436 °C): $L \rightarrow \alpha$ (Mg) + $Mg_{17}Al_{12}$.

It is evident from Figure 2 that the major difference between the two alloys occurs after the solid fraction of about 95%, when the AM30 alloy completes its solidification at the eutectic temperature of 436 °C (solidus) but the AZ31 alloy still forms the lower temperature ternary eutectic Mg–Al–Zn phases (φ and τ), with a much

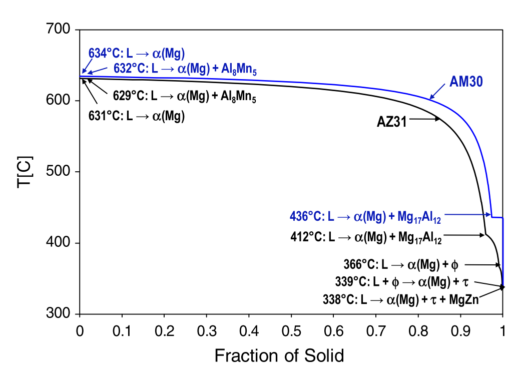

Figure 2. Solidification curves (temperature vs. solid fraction) of AZ31 and AM30 alloys based on the Scheil simulation of the quaternary Mg–Al–Zn–Mn system and the ternary Mg–Al–Mn system, respectively.