ABSTRACT

The primary aim of the present study is to develop lean Mg alloys for elevated temperature automobile applications. Towards this, the microstructure evolution and its implications on the room temperature mechanical properties and elevated temperature creep properties were studied in lean Mg-Zn-Al and lean Mg-Al-Ca-Mn alloys, in as-cast, thermomechanically and thermally treated conditions. Since the as-cast Mg-3Zn-1Al alloy exhibits poor room temperature mechanical properties, it was subjected to hard plate hot forging (HPHF) at different temperatures to modify the microstructure through dynamic recrystallization (DRX). The DRX fraction increases from 22±6% to 73±5% as the temperature is raised from 523 K to 623 K, reducing the fraction of deformed grains and subsequently, the yield strength (YS ~232±4 MPa to ~168±2 MPa). However, the basal texture is weakened due to the random orientations of the DRX grains and consequently, the ductility is improved in the specimen forged at 623 K (uniform elongation, UEl ~10.7±1.2%). At 723 K, grain growth is initiated which increases the grain size and re-strengthens the basal texture, resulting in decrease of both YS (151±7 MPa) and ductility (UEl ~7.1±1.1%) of the corresponding specimen. Solution annealing results in significant grain growth, second phase dissolution and texture weakening, which decreases the YS, but improves the ductility significantly, in all the HPHF specimens. In order to optimize the Mg-Al-Ca-Mn alloy composition, the Ca/Al ratio was varied within ~0.06-2.21, which is observed to not only dictate the second phase evolution, but also control the solid solution environment in the as-cast alloys. Consequently, despite having coarser grains (354±43 μm), the as-cast Mg-0.9Al-0.6Mn-0.1Ca alloy exhibits higher strength (YS ~130±5 MPa), owing to greater contribution from solid solution strengthening as well as precipitation strengthening from the $Mg_{17}Al_{12}$ phase. The mechanical properties deteriorate in the alloys with higher Ca/Al ratio owing to the strong connected networks of hard and brittle Mg_2Ca phase, which promote initiation and propagation of cracks. Post HPHF, the grain size is significantly reduced due to DRX, while typical basal fiber textures are developed in the Mg-Al-Ca-Mn alloys. The Mg-1.3Ca-0.8Al-0.4Mn alloy exhibits maximum YS (~167±3 MPa) predominantly due to the larger strengthening contributions from its finer grains and precipitates. However, despite having weaker basal texture, this specimen displays poor ductility (UEl ~2.7±1.0%) owing to the networks of coarse Mg_2Ca particles. The Mg-1Al-0.28Ca-0.13Mn alloy, which shows optimum combinations of strength and ductility in both as-cast (YS ~90±7 MPa and UEl ~4.8±1.6%) and HPHF conditions (~132±12 MPa and UEl ~5.0±1.0%), was selected for thermal treatments to attain further strengthening. The aging treatment of the cast Mg-1Al-0.28Ca-0.13Mn alloy led to the formation of fine Al_2Ca precipitates from pre-existing $(Mg,Al)_2Ca$ phases, along with evolution of new $(Mg,Al)_2Ca$ particles. Simultaneously, the size, area fraction and interfacial lattice misfit of the nano-sized Al_8Mn_5 precipitates increase with aging duration. These precipitates, depending on their coherency with the matrix, are either sheared off or bypassed by the dislocations, which predominantly dictate the strength in these specimens. Thus, the relatively smaller size (~16±4 nm), higher area fraction (~2.4±09%), and larger misfit (~14±9%)

of the semi-coherent Al_8Mn_5 precipitates result in higher strengthening (YS ~133±5 MPa and UTS ~190±9 MPa) in the peak-aged specimen. Contrarily, the coarser $(Mg,Al)_2Ca$ particles act as crack-initiating sites and deteriorate the ductility during the later stages of aging. The HPHF specimen of the Mg-1Al-0.28Ca-0.13Mn alloy was subjected to aging treatment directly as well as after an intermediate solution-annealing treatment. While evolution of very fine Al_8Mn_5 precipitates takes place during direct peak-aging, a large proportion of the fine precipitates dissolves during the solution annealing treatment after HPHF. However, due to the formation of new precipitates, the area fraction of the fine Al_8Mn_5 precipitates increases during peak-aging of the 'HPHF+solution-annealed' specimen. The fine DRX grains (originated during HPHF) and the finer Al_8Mn_5 precipitates result in significant strengthening (YS ~162±14 MPa) in the directly peak-aged HPHF specimen. In the 'HPHF+solution-annealed' specimen, the strength is considerably decreased (~88±2 MPa) owing to grain growth and dissolution of precipitates, but the ductility is significantly improved (11.8±1.7%) due to texture weakening. During peak aging of this specimen, strength is further improved (~105±1 MPa) owing to the relatively higher fraction of the nano-sized Al_8Mn_5 precipitates. Few specimens from both the Mg-Zn-Al and Mg-Al-Ca-Mn systems, selected on the basis of the microstructure and room temperature tensile properties, were subjected to compressive creep tests at 448 K under 50 MPa stress. The grain size is observed to play a dominant role in dictating the creep performance in the Mg-3Zn-1Al alloy. Thus, the solution-annealed specimens having larger grain size exhibit lower steady state strain rate (SSSR) than the HPHF specimens. Similarly, the as-cast, 'HPHF+solution-annealed' and 'HPHF+solution-annealed+peak-aged' specimens of the Mg-1Al-0.28Ca-0.13Mn alloy exhibit better creep performance due to the presence of much coarser grains. Importantly, both the as-cast and the 'HPHF+solution-annealed' specimens exhibit relatively better creep performance than their respective peak-aged counterparts, due to dynamic evolution of fine Al_8Mn_5 precipitates during creep.

Keywords: Aging; Casting; Creep; Dislocations; Dynamic recrystallization; Grain growth; Grain size; Hard plate hot forging; Lean Mg-Al-Ca-Mn alloys; Lean Mg-Zn-Al alloy; Microstructure; Precipitates; Solid solution; Solution annealing; Tensile properties; Texture; Twins; Work hardening.