Materials and Design 55 (2014) 300–308

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Forgeability test of extruded Mg–Sn–Al–Zn alloys under warm forming conditions

Jonghun Yoon *, Sunghyuk Park

Korea Institute of Material Science, 797 Changwondaero, Changwon, Gyeongnam 642-831, Republic of Korea

ARTICLE INFO

Article history:
Received 14 March 2013
Accepted 2 October 2013
Available online 10 October 2013

Keywords:
Magnesium alloy
Mg–Sn–Al–Zn alloy
Mg–Al–Zn alloy
Forgeability
T-shape forging
Orientation imaging microscopy

ABSTRACT

Magnesium (Mg) alloys have been thoroughly researched to replace steel or aluminum parts in automotives for reducing weight without sacrificing their strength. The widespread use of Mg alloys has been limited by its insufficient formability, which results from a lack of active slip systems at room temperature. It leads to a hot forming process for Mg alloys to enhance the formability and plastic workability. In addition, forged or formed parts of Mg alloys should have the reliable initial yield and ultimate tensile strength after hot working processes since its material properties should be compatible with other parts thereby guaranteeing structural safety against external load and crash. In this research, an optimal warm forming condition for applying extruded Mg–Sn–Al–Zn (TAZ) Mg alloys into automotive parts is proposed based on T-shape forging tests and the feasibility of forged parts is evaluated by measuring the initial yield strength and investigating the grain size in orientation imaging microscopy (OIM) maps.

1. Introduction

Magnesium (Mg) alloys have been of great interest for a variety of applications, including the automotive and electronics industries, due to their high specific strength, excellent thermal conductivity, and recycling capability in comparison with commonly used aluminum alloys and steels for structure materials. However, the widespread use of Mg alloys has been limited by its insufficient formability and low fatigue durability [1–3]. Due to the hexagonal close packed (HCP) structure of Mg alloys, only a limited number of deformation accommodation mechanisms are available at room temperature, which leads to a hot forming process to overcome these obstacles [4]. Mg alloys are currently used in relatively small quantities for automotive parts since, generally, their processing is limited to die casting which can have reduced manufacturing cost compared with steels. However, there exist casting defects and porosity which tend to degrade the mechanical properties of Mg forming parts [5,6].

Many researchers have focused on Mg forging since it does not only provide improved mechanical properties of forming parts but also enable high dimensional accuracy compared to die casting at the elevated temperatures. Mg forging applications include steering knuckles, control arms, and high-strength road wheels [7] in automobiles. Shan et al. [8] proposed a complex shape forging technology by adopting fully enclosed die forging and a combined female die. Wang et al. [9] imposed a pre-strain to the initial billet before the forging process to decrease the forming load and improve the microstructure by dynamic recrystallization (DRX), which enables AZ80 alloy wheels and AZ31 alloy brackets being forged successfully for near-net-shape forming. Rao et al. [10] has isothermally forged a part with rib–web shape with AZ31B direction at speeds of 0.01–10 mm/s in the temperature range of 300–500 °C to validate the results of materials models involving kinetic analysis and processing maps.

A severe compressive force during Mg forging at elevated temperature causes the part to have a preferred orientation crystallographically aligned along the strain direction and induces DRX, which affects the mechanical properties of the forged part significantly. Therefore, it is required to correlate the microstructural evolution, such as DRX and grain growth, with mechanical properties of deformed parts during the forging and heat treatment process. Ogawa et al. [11] investigated the workability of ZK60 by conducting a simple upsetting test and the results are applied to precision backward extrusion and extruded cup forging at elevated temperatures. Skubisz et al. [12] showed that closed-die forging is a versatile test of forgeability in a complex state of stress and strain. Guan et al. [13] demonstrated the plasticity diagram of AZ70 under tensile stress for evaluating hot forgeability, which enables a head shell forging possessing the desired microstructure and good combined mechanical properties compared with an Al alloy shell. Zheng et al. [5] studied the forgeability of as-cast NZ30K alloy prepared by direct chill (DC) casting which was evaluated by the ratio between elongation and ultimate tensile strength (UTS). High temperature creep tests were also performed and the creep properties of NZ30K were compared with those of AZ91 alloy.

* Corresponding author. Tel.: +82 (55) 280 3839; fax: +82 (55) 280 3849.
E-mail address: jhyoon@kims.re.kr (J. Yoon).

0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.10.008

Table 1
Chemical composition of the investigated Mg alloys.

Mg alloy	Chemical composition (%)				
	Sn	Al	Mn	Zn	etc.
AZ61	–	6.5	0.15	1.0	92.35
AZ80	–	8.5	0.12	0.5	90.88
TAZ541	5.0	4.0	–	1.0	90.00
TAZ711	7.0	1.0	–	1.0	91.00
TAZ811	8.0	1.0	–	1.0	90.00

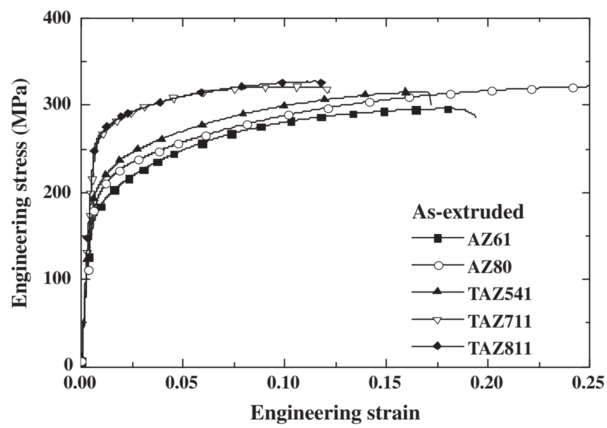

Fig. 1. Comparative tensile tests of Mg alloys at room temperature.

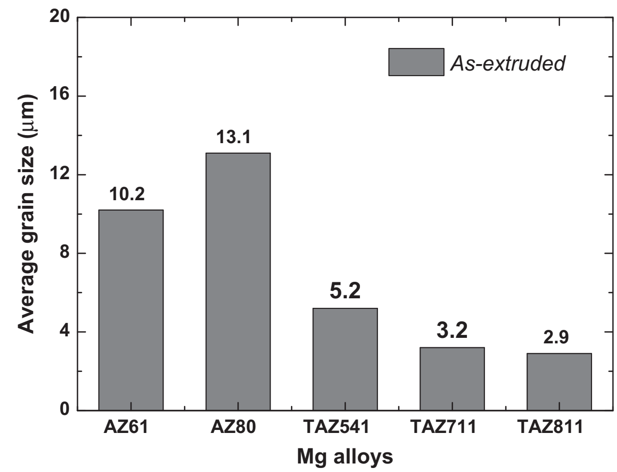

Fig. 2. Comparison of initial grain sizes of various Mg alloys.

Hakamada et al. [14] studied tensile properties of a forged Mg–Ca alloy and investigated the effect of Ca addition on fracture elongation. They reported that the forged Mg–Ca alloy shows a large elongation of 284% at 573 K because stress concentration at second phase particles could be relaxed by diffusion. Dai et al. [15] investigated the anisotropy of Mg alloy using uniaxial compression experiments in which the texture, constitutive relationship, and fracture characteristics are related to the competition between twinning and slipping at different temperatures and strain rates during the plastic deformation. Deng et al. [16] examined the effect of deformation parameters on the strain hardening rate, strain rate sensitivity, microstructural evolution and fracture morphology in the by uniaxial tensile tests with the temperature range of 523–723 K and strain rate range of 0.05–0.0005/s with the hot-rolled AZ31 magnesium alloy. Changizian et al. [17] demonstrated the effects of the temperature and strain rate on hot deformation behavior in terms of the Zener–Hollomon equation for the AZ81 magnesium alloy considering strain effects. Quan et al. [18] evaluated the workability of wrought AZ80 magnesium alloy by means of processing maps on the basis of dynamic materials model (DMM), constructed from experimentally generated flow stress variation with respect to strain, strain rate and temperature. Wu et al. [19] showed that the excellent tensile ductility of the Mg–2.74Gd–1.06Zn alloy sheets is mainly attributed to its low intensity of (0002) pole figure, instead of the nonbasal texture type by controlling the texture and the grain size with hot rolling, forging and annealing treatments. Chalay-Amoly et al. [20] showed that the microstructural features such as grain size, mechanical twins, and γ-second phases are strongly affected by applying backward extrusion with AZ91 magnesium alloy. Xia et al. [21] demonstrated the microstructure and texture evolution of coarse-grained Mg–Gd–Y–Nd–Zr alloy during hot compression by EBSD analysis.

Concerning applications of Mg-based materials, this represents another main issue for replacing automobile inner or external parts by Mg alloys, since the leading automakers have concentrated on light-weight design for improving the fuel efficiency of automobiles [22–24]. To cope with massive demands for automotive parts employing Mg alloys, newly designed Mg alloys have been developed to satisfy higher strength and creep resistance whose mechanism at low temperature is basal slip within grains and sub-grain formation, while at higher temperatures, a diffusion dependent mechanisms become predominant [7].

The Mg–Sn alloy system demonstrates an enhanced heat-resistance since the secondary phase, Mg_2Sn, has a high melting temperature [25]. Sasaki et al. [26] discovered that a Mg–Sn–Zn–Al alloy which was extruded at a very low ram speed of 0.1 mm/s with an extrusion ratio of 20 shows high strength and low tension–compression yield asymmetry at room temperature due to the fine-grained microstructure and the presence of fine Mg_2Sn precipitates [25,26]. Tang et al. [25] reported on the effect of Zn content on the microstructural characteristics and mechanical properties of indirectly extruded Mg–5Sn–*x*Zn alloys in which the yield point asymmetry ratio increases from 0.74 to 0.86 with increasing portion of zinc due to the presence of finer particles of the Mg_2Sn and MgZn phase, respectively. Cheng et al. [27] found out that an addition of Ce improves the tensile strength compared to the Ce-free alloy which is associated with a homogeneous fine-grained structure and a dense distribution of precipitates. Likewise, Park et al. [28] investigated the tensile properties of extruded Mg–Sn–Al–Zn alloys at elevated temperature and found that the low-temperature superplasticity is attributed to the fine-grained microstructure, which contained thermally stable Mg_2Sn precipitates.

In this paper, three extruded TAZ alloys, specifically 541, 711, and 811 (Mg$-x$ wt.% Sn$-x$ wt.% Al$-x$ wt.% Zn) were produced with a diameter of 15 mm under an extrusion ratio of 25 to evaluate their forgeability at various forging temperatures and strain rates using exemplary T-shape forging. The results were compared with conventional AZ61, 80 alloys. The forgeability of each Mg alloys is evaluated by measuring the final dimensions of the forged parts using 3D-scanning, which provides an optimal forging condition for Mg alloys at elevated temperatures. In order to examine the change and variation of the mechanical properties of Mg alloys during warm forging, tensile tests were conducted at quasi-static conditions since the mechanical strength plays an important role in deciding whether the forged Mg parts can be successfully implemented in an autobody. The effect of warm forging fabrication on the mechanical properties has been examined by investigating the grain refinement and growth due to DRX, on the basis of OIM experiments.