



Compressive strength and hot deformation behavior of TX32 magnesium alloy with 0.4% Al and 0.4% Si additions

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ABSTRACT

Mg–3 wt.%Sn–2 wt.%Ca (TX32) alloy has good corrosion and creep resistance although its strength does not match that of AZ31 alloy. In this paper, the influence of additions of 0.4 wt.%Al and 0.4 wt.%Si on the compressive strength and hot working characteristics of TX32 is reported. Although the room temperature compressive strength improved marginally with the alloying additions, the drop in higher-temperature strength is significant. By comparing with the alloy having only 0.4% Al, it is inferred that the Si addition is responsible for this deterioration. The hot working behavior is characterized by processing maps which revealed that TX32 exhibits two domains of dynamic recrystallization occurring in the temperature and strain rate ranges: (1) 300–350 °C and 0.0003–0.001 s^{−1} and (2) 390–500 °C and 0.005–0.6 s^{−1}. In Al and Si containing TX32, both the domains moved to higher temperatures and the flow instability is reduced thereby improving the hot workability. In both the domains, the apparent activation energy is 177 kJ/mol, which is higher than that for self-diffusion in magnesium implying that there is a significant contribution from the back stress generated by the hard particles present in the matrix.

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1. Introduction

Their light weight is the main reason that makes Mg based alloys attractive for components in aerospace and automobile applications. However, many of the wrought alloys like Mg–3Al–1Zn have inferior corrosion and creep properties and to improve these two properties newer Mg–Sn–Ca alloys (TX series) are being developed [1–3]. In this system, Sn forms a solid solution with Mg and imparts corrosion resistance while Ca enhances high temperature creep strength by forming CaMgSn intermetallic particles. The first and foremost alloy in this system is Mg–3Sn–1Ca (TX31), which was characterized as regards its corrosion resistance and processability [4–6]. The creep resistance of this alloys can be further improved by increasing the Ca content to 2% but with a small compromise of corrosion properties [3,7]. In the microstructure of Mg–3Sn–2Ca [3], intermetallic particles of CaMgSn form mostly in the matrix and Mg₂Ca phase forms at the grain boundaries both of which are beneficial in enhancing the creep strength. However, there is a need to strengthen the alloy further to make it a candidate material for structural applications. For this purpose, alloying with aluminum and silicon is considered to be attractive since Al causes solid solu-

tion strengthening of Mg as there is a significant difference in the atomic diameters of Mg and Al, while Si forms intermetallic particles that can enhance the creep strength. With this in view, Mg–3 wt.%Sn–2 wt.%Ca–0.4 wt.%Al–0.4 wt.%Si alloy has been designed and chosen for this investigation. The aim of the present investigation is to evaluate the compressive strength and hot working characteristics of this alloy with a view to understand the effect of the combined additions of Al and Si to TX32. For this purpose, the compressive strength of Mg–3Sn–2Ca–0.4Al–0.4Si is measured in the temperature range 25–250 °C and the hot working behavior is evaluated in the temperature range 300–500 °C. It is proposed to compare the behavior of this alloy with that of Mg–3Sn–2Ca and Mg–3Sn–2Ca–0.4Al.

The hot working behavior has been characterized with the help of the standard kinetic approach [8] as well as processing maps [9,10]. The standard kinetic rate equation relating the steady state flow stress (σ) to strain rate ($\dot{\epsilon}$) and temperature (T) is given by [8]:

$$\dot{\epsilon} = A\sigma^n \exp \left[-\frac{Q}{RT} \right] \quad (1)$$

where A = constant, n = stress exponent, Q = activation energy, and R = gas constant. The rate-controlling mechanisms are identified on the basis of the activation parameters n and Q .

Processing maps are based on the Dynamic Materials Model [11], the principles of which were described in earlier publica-

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tions [9,12]. Briefly, the work-piece undergoing hot deformation is considered to be a dissipator of power and the strain rate sensitivity (m) of flow stress is the factor that partitions power between deformation heat and microstructural changes. The efficiency of power dissipation occurring through microstructural changes during deformation is derived by comparing the non-linear power dissipation occurring instantaneously in the work-piece with that of a linear dissipater for which the m value is unity, and is given by:

$$\eta = \frac{2m}{(m+1)} \quad (2)$$

The variation of efficiency of power dissipation with temperature and strain rate represents a power dissipation map which is generally viewed as an iso-efficiency contour map. Further, the extremum principles of irreversible thermodynamics as applied to continuum mechanics of large plastic flow [13] are explored to define a criterion for the onset of flow instability given by the equation for the instability parameter $\xi(\dot{\epsilon})$:

$$\xi(\dot{\epsilon}) = \frac{\partial \ln[m/(m+1)]}{\partial \ln \dot{\epsilon}} + m \leq 0 \quad (3)$$

The variation of the instability parameter as a function of temperature and strain rate represents an instability map which delineates regimes of instability where $\xi(\dot{\epsilon})$ is negative. A superimposition of the instability map on the power dissipation map gives a processing map which reveals domains (efficiency contours converging toward a peak efficiency) where individual microstructural processes occur and the limiting conditions for the regimes (bounded by a contour for $\xi(\dot{\epsilon}) = 0$) of flow instability. Processing maps help in identifying temperature–strain rate windows for hot working where the intrinsic workability of the material is maximum (e.g. dynamic recrystallization (DRX) or superplasticity) and also in avoiding the regimes of flow instabilities (e.g. adiabatic shear bands or flow localization).

2. Experimental

Mg–3 wt.%Sn–2 wt.%Ca–0.4 wt.%Al–0.4 wt.%Si alloy was prepared using 99.99% pure Mg, 99.96% pure Sn, 98.5% pure Ca, 99.9% Al and 99.9% Si. The alloy, molten at about 720 °C, was kept under a protective cover of Ar + 3% SF₆ gas before casting in a pre-heated permanent mold (200 °C) to obtain cylindrical billets of 100 mm diameter and 350 mm length.

Cylindrical specimens of 10 mm diameter and 15 mm height were machined from the as-cast billet for compression testing. For inserting a thermocouple to measure the specimen temperature as well as the adiabatic temperature rise during deformation, the specimens were provided with a 1 mm diameter hole machined at mid height to reach the centre of the specimen.

For the purpose of evaluating the compressive strength of the alloy, compression tests were conducted at a strain rate of 0.0001 s^{−1} and in the temperature range 25–250 °C using a computer-controlled servo-hydraulic testing machine. The data for developing processing maps were obtained in isothermal uniaxial compression tests conducted at constant true strain rates in the range 0.0003–10 s^{−1} and temperature range 300–500 °C. Details of the test set-up and procedure are described in earlier publication [14]. Constant true strain rates during the tests were achieved using an exponential decay of actuator speed in the servo hydraulic machine. Graphite powder mixed with grease was used as the lubricant in all the experiments. The specimens were deformed up to a true strain of about 1.0 and then quenched in water. The load–stroke data were converted into true stress–true strain curves using standard equations. The flow stress values were corrected for the adiabatic temperature rise at different temperatures and strain rates and this correction was less important at lower strain rates

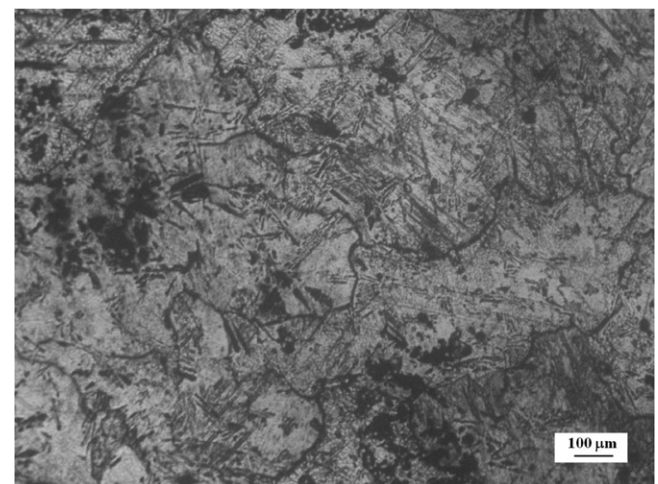
and higher temperatures. The deformed specimens were sectioned in the center parallel to the compression axis and the cut surface was mounted, polished and etched for metallographic examination. All the specimens were etched with an aqueous solution containing 3% picric acid. The grain size in the deformed specimens was measured using linear intercept method and an average grain diameter was arrived at on the basis of at least 100 measurements. The scatter in the data was estimated to be about ±5%.

3. Results and discussion

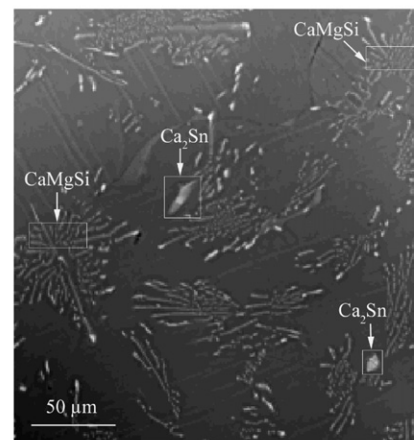
The microstructure of the starting material in cast condition is shown in Fig. 1(a) which exhibits very large grains (about 500 μm diameter) with dendritic features. The microstructure has several intermetallic particles, mainly CaMgSi and Ca₂Sn, as marked on the SEM image in Fig. 1(b). Though the basic morphology of these particles is somewhat similar, particles that appear bright are Ca₂Sn while the other clusters of particles are CaMgSi.

3.1. High temperature strength

The variation of the ultimate compressive strength of Mg–3Sn–2Ca–0.4Al–0.4Si alloy with temperature in the range 25–250 °C obtained at a strain rate of 0.0001 s^{−1} is shown in Fig. 2. A strain rate slower than that used for generating processing maps



(a)



(b)

Fig. 1. Initial microstructure of Mg–3Sn–2Ca–0.4Al–0.4Si alloy in as-cast condition: (a) Optical micrograph, and (b) Back-scattered electron image, with intermetallic particles marked.

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