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Impression Creep Behaviour of Extruded Mg-Sn Alloy

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ABSTRACT:

Mg-Sn alloys contain thermally stable Mg_2Sn phase, and are proposed as heat-resistant alloys for automobile engine applications. In this study, the creep behaviour of Mg-5Sn alloy was investigated using impression creep technique. The impression creep tests were carried out under constant punching stress in the range of 80-320 MPa at temperatures 373-573 K, for dwell times up to 5 hours. The results highlight that creep of Mg-5Sn alloy was load and temperature dependent, i.e. increasing the load and temperature resulted in larger creep deformation and hence to higher creep rates. From the creep curves, the stress exponent and the activation energy were estimated and the creep mechanism was identified.

KEYWORDS:

Magnesium alloys; Mg-5Sn alloy; Impression creep; Creep rate; Temperature; Stress

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1. Introduction

Magnesium (Mg) alloys are the lightest available structural commercial alloys with a wide range of potential applications in the aerospace and automotive industries. In recent years, many efforts have been carried out to enhance the high-temperature properties of magnesium alloys to improve their application potential at these temperatures [1, 2]. Amongst the high temperature properties, creep behaviour of Mg-alloys is the most important. Conventional tensile creep tests require samples with larger dimensions. On the other hand, impression creep tests require small samples that have creep characteristics comparable to the conventional creep test data. It should be noted that most of the creep studies on magnesium are based on Mg-Al alloys, which usually show a drastic drop in their high-temperature mechanical properties and creep resistance with increasing temperature above 150°C (i.e. have low thermal stability). Research works on Mg-creep using indentation tests that show the creep behaviour of Mg-Al based alloys are given in [3-7].

In order to overcome the low thermal stability of Mg-Al alloys, new alloys are being developed. These alloys include those with rare earth metal (RE) additions (with or without Al), Zr-additions, and most recently Sn-addition [8-11]. RE and Zr-based Mg-alloys have high temperature resistance but however are very expensive. On the other hand, Mg-Sn alloys are cost effective, and in addition are expected to exhibit high temperature resistance due to the presence of Mg_2Sn phase (melting point of Mg_2Sn is 770°C, whereas $Mg_{17}Al_{12}$ is ~410°C). Therefore, in this study, the creep characteristic of Mg-5Sn alloy has been undertaken. Impression creep tests have been conducted and the effect of applied stress and temperature on the creep behaviour of Mg-5Sn alloy has been investigated.

2. Experimental procedure

Mg-5Sn alloy was prepared using the Disintegrated Melt Deposition (DMD) technique at the National University of Singapore (NUS). The DMD technique adopts the simultaneous vortex stirring of the melt and its disintegration, with argon (Ar) gas for inert atmosphere and for melt disintegration, resulting in a high yield process and fine grain size material. The detailed experimental procedure is described elsewhere [12]. High purity Mg and Sn were used to prepare the alloy. Cylindrical billets of 36 mm diameter cut from the deposited Mg-5Sn alloy ingots were soaked at 400°C for 1 h. The billets were hot extruded at 350°C using a 150 ton hydraulic press at an extrusion ratio of 20.25:1 to produce rods of 8 mm diameter that were used for further characterization [12]. Optical and scanning electron microscopy studies were also carried out on the Mg-5Sn extruded alloy to study its microstructure.

For the impression creep tests, cylindrical samples with 6mm diameter and 6 mm height were prepared from the extruded rod. Impression creep tests were carried out using an impression creep testing machine (Spranktronics, Bangalore). Fig. 1(a) shows the impression creep testing machine. It contains constant-load equipment, a temperature controller and a computer-controlled data acquisition system. In this method, by the application of a constant load (stress) at specific temperatures, the indenter is impressed on the sample. In the current work, tungsten carbide cylindrical punch (diameter: 1.5mm) is used as the indenter (inset in Fig. 1(a)). The indentation creep tests were performed under different load (ranging from 80 MPa to 320 MPa) and different temperature (ranging from 373 K to 573 K) for dwell times up to 18000 seconds (up to ~5 hours). Due to the application of the load, the impression is made on the sample by the indenter Fig. 1(b) and the impression depth is acquired automatically as a function of time.

Fig. 1(a): The impression creep tester and indenter

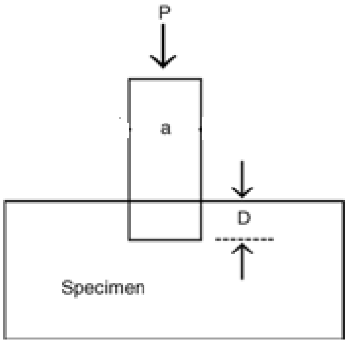


Fig. 1(b): Schematic of the impression creep test

3. Results and discussion

Optical micrograph of the Mg-5Sn alloy in Fig. 2(a) shows that the alloy has an average grain size ~2.5mm, aspect ratio ~1.6 and roundness ~1.5. Figs. 2(b) and (c) are the scanning electron micrographs revealing the second phase morphologies that have two different particle morphologies, viz., polygonal shaped particles (marked ‘A’) 2 to 4mm and submicron-sized lath/rod-like particles (marked ‘B’ - length 500nm to 1mm; diameter < 200nm).

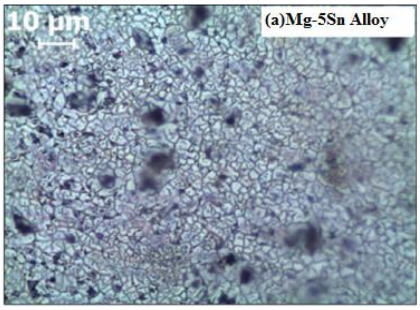


Fig. 2(a): Optical micrograph of Mg-5Sn alloy

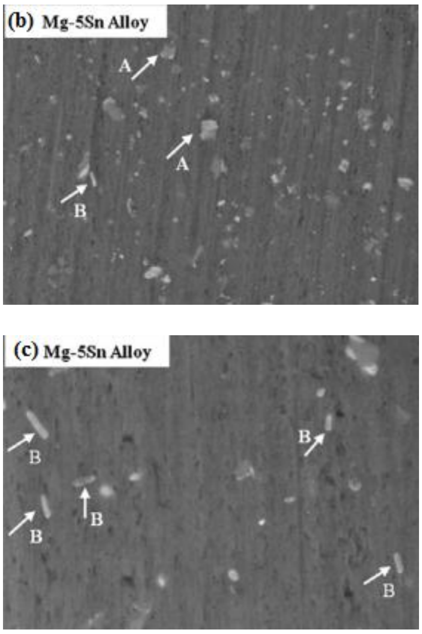
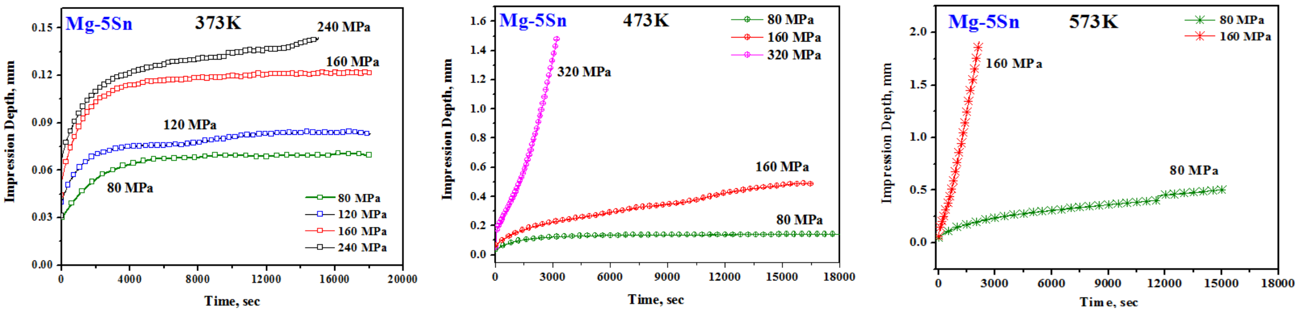


Fig. 2(b) & (c) SEM images showing the polygonal and lath/rod-like morphology of the Mg_2Sn phase in the Mg-5Sn alloy

Impression creep curves of Mg-5Sn alloy at different loads (80 MPa to 320 MPa) and different temperatures 373 K to 573 K are presented in this section. The creep curve is expressed in the form of depth of impression vs. time. Fig. 3 shows the depth vs. time curves obtained in the present work. These curves indicate that at constant temperature, increasing stress condition results in higher penetration depth. It should be noted that usually in a creep test, creep increases with time (primary creep) and reaches a steady state (secondary creep) and finally increases rapidly with time until fracture occurs (tertiary creep). The impression creep test being compressive in nature, third stage of the curve does not occur (no fracture of specimen).

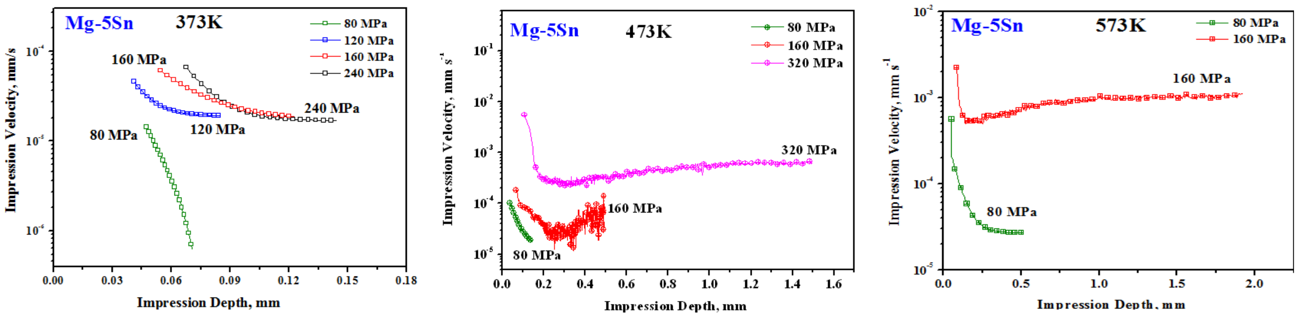


(a) Test temperature = 373 K (b) Test temperature = 473 K (c) Test temperature = 573 K

Fig. 3: Impression depth vs. Time of Mg-5Sn alloy for various applied stress values

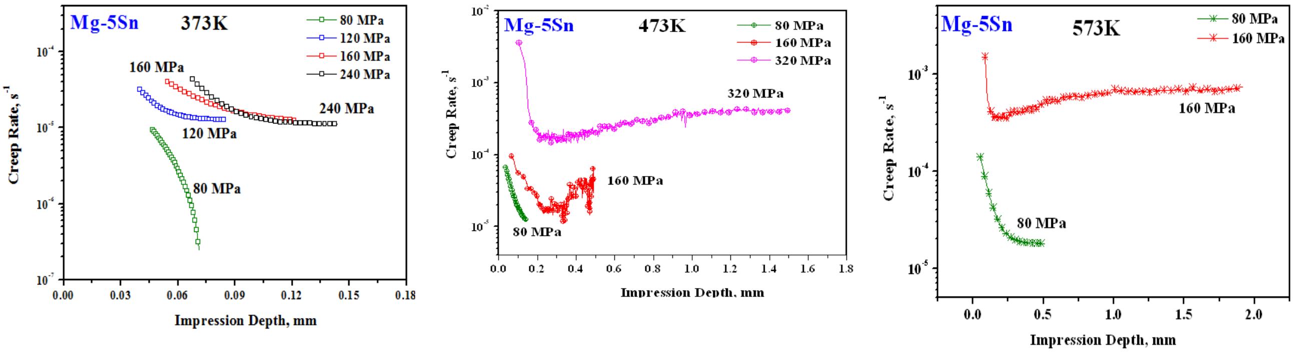
To ensure that a steady state creep regime has been reached, the impression velocity (V_{imp} = dh/dt) is plotted against impression depth Fig. 4. The results indicate that the impression velocity initially decreases with depth and reaches a steady state value after a particular depth at any gives stress or temperature. Also, the steady state impression velocity increases with increase in temperature and applied stress.

From the impression velocity, the steady state creep values can be obtained by plotting V_{imp}/2a (minimum creep rate), where v is the impression velocity and 2a is the diameter of the indenter [1]. The results indicate that the creep rate increases with increase in temperature and stress levels, as shown in Fig. 5, and is possibly due to the increase rate of atomic diffusion at elevated temperatures [13].



(a) Test temperature = 373 K (b) Test temperature = 473 K (c) Test temperature = 573 K

Fig. 4: Impression velocity vs. Impression depth of Mg-5Sn alloy for various applied stress values



(a) Test temperature = 373 K (b) Test temperature = 473 K (c) Test temperature = 573 K

Fig. 5: Creep rate vs. Impression depth of Mg-5Sn alloy for various applied stress values

From the creep data, the creep mechanism can be determined by calculating the values of the stress exponent (n) and the creep activation energy (Q). According to the equation suggested by Chu and Li [2],

$$V_{imp} = 2aA(\sigma_{imp}/3.3)^n \exp(-Q/RT) \quad (1)$$

Here, V_{imp} is the steady state impression velocity, a is the punch radius, A is a material parameter, σ_{imp} is the punching stress, Q is the activation energy, T is the absolute temperature in K, R is the gas constant and n is the stress exponent [13]. It should be noted that shear modulus is typically a function of testing temperature and for pure Mg it is given by,

$$G(MPa) = 19{,}200 - 8.6T(K) \quad (2)$$

In order to correlate the impression and tensile creep data, the equivalent stress and strain rate can be evaluated from the impression velocity (V_{imp} = dh/dt), the impression stress under the punch $\left(\sigma_{imp} = 4F/pF^2\right)$ at a given load F, and punch diameter ϕ as,

$$\varepsilon' = A(GbD/kT)(\sigma/G)^n \exp(-Q/RT) \quad (3)$$

$$\sigma = \sigma_{imp}/c_1 \quad and \quad \varepsilon' = (dh/dt)/\Phi c_2 = V_{imp}/\Phi c_2 \quad (4)$$

Therefore, inserting Eqn. (4) into Eqn. (3), the relationship between the impression velocity and the applied stress is given by,

$$V_{imp}\, T/G = B(Bd/k)(\sigma_{imp}/G)^n \exp(-Q/RT) \quad (5)$$

By calculating the values of n and Q, it is possible to determine the dominant creep mechanism for different stress and temperature conditions. From Eqn. (1), the stress exponent (n) and the activation energy (Q) can be obtained from the slopes of the linear fit of the variation of normalized impression minimum velocity with impression stress and 1/T respectively.

Fig. 6(a) shows the variation of steady state creep rate as a function of punching stress (in a ln-ln scale) at various test temperatures. Dependence of steady state creep rate on temperature is shown in Fig. 6(b) (in a ln-ln plot) for varying stresses. It can be seen from Fig. 6(a) that the exponent, n, varies between <1 and ~6. Considering the average value of n as ~3, the dominant creep mechanism is identified to be creep controlled by dislocation glide [3]. Similarly, from Fig. 6(b), from the slope of the linear fit, it can be seen that the activation energy is ~ 40-42 kJ/mol. It should be noted that the activation energy for self diffusion of Mg is 134 kJ/mol [5]. In the present case, the activation energy is lower. Hence the dominant mechanism is due to grain boundary flow leading to grain boundary sliding [5]. Further, as the activation energy decreases slightly with increasing punching stress, this indicates that at higher stresses, creep occurs due to stress-assisted activation process [5].

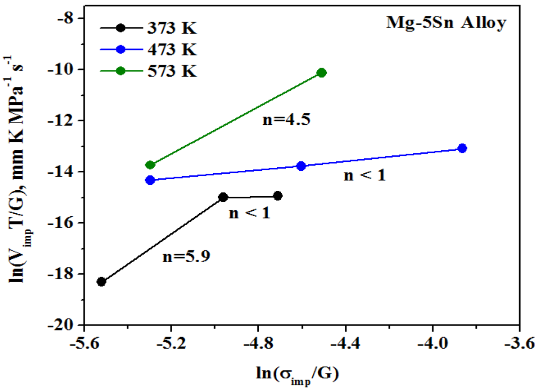


Fig. 6(a): Normalized impression minimum velocity as a function of punching stress at different temperatures

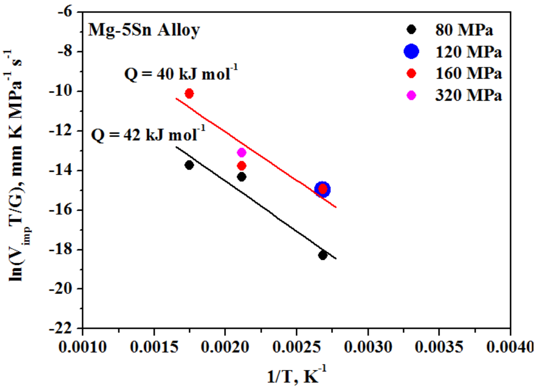


Fig. 6(b): Normalized impression minimum velocity as a function of temperature at different stresses

4. Conclusions

Creep of Mg-5Sn alloy has increased with increasing load and temperature. The impression velocities and the steady state creep rate were found to be directly dependent on stress and temperature. The calculation of the stress exponent, n, and the activation energy, Q, shows that the creep mechanism is not the same at all temperature and stress range. Grain boundary sliding and stress-assisted activation were dominant at with stress variation, whereas temperature variation gives rise to glide mechanism.

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