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Constitutive analysis of wrought magnesium alloy Mg–Al4–Zn1

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Stress–strain data were collected from uniaxial compression tests over a wide range of strain rates and then corrected for deformation heating. The effect of the data correction on the constitutive behaviour, incorporating a strain-dependent parameter, of wrought magnesium alloy Mg–Al4–Zn1 was evaluated. The results show that the strain-dependent analysis provides a constitutive equation that leads to a good agreement between the calculated and measured flow stresses in the relevant temperature range.

Keywords: Magnesium; Hot workability; Constitutive analysis; Compression testing

Magnesium is a lightweight material with a high specific strength. As such, it has a great potential to be used in automobiles to reduce vehicle weight and hence fuel consumption. However, the use of wrought magnesium alloys has so far been restricted, partly because of their low formability due to the small number of slip systems available for deformation. It is a challenge to explore the deformation limits of wrought magnesium alloys and to provide the metal-forming industry with well-defined material-processing opportunities.

Process modelling is a powerful tool to predict material behaviour under specified deformation conditions. The reliability of the output from modelling depends to a large extent on the trustworthiness of input data. The material data necessary for the modelling of a forming process in terms of a relationship between flow stress, strain, strain rate and temperature can be obtained from hot-working tests at a number of temperatures and strain rates for a consistent representation of deformation behaviour.

At present, the stress–strain data of many wrought magnesium alloys at high-strain rates $>10\ s^{-1}$, typical of industrial bulk-forming processes, are unavailable. This is partly due to the limitation of hot-working tests not attaining high-strain rates. Industrial forming processes need to achieve large reductions over a short time to maximize productivity. It is therefore important to understand the hot deformation behaviour of magnesium alloys in the high-strain rate regime.

Either uniaxial compression testing or torsion testing can be used to investigate the deformation behaviour of a wrought magnesium alloy. The feasibility of applying high-strain rates makes hot uniaxial compression testing more suitable for constitutive analysis applicable to industrial bulk-forming processes, as a local strain rate of $50\ s^{-1}$ or even higher may be reached, e.g. during extrusion.

Previous studies have demonstrated the usefulness of the data generated from compression tests for modelling purposes [1,2]. Similar tests were performed to characterize the response of magnesium alloys to hot deformation [3–5]. In most previous investigations of the hot deformability of magnesium alloys, the stress–strain data collected were used uncorrected to establish constitutive equations [6–10]. In the plots of $\ln\sigma$ vs. $1000/T$, the temperature at the beginning of the deformation was used with no indication of the actual temperature of the specimen during testing. In fact, at a low strain rate ($<0.1\ s^{-1}$), the specimen temperature may change during testing due to the increasing area of contact with the anvils, which can cause a noticeable change in the flow stress. At an intermediate strain rate and a high-strain rate ($>1\ s^{-1}$), deformation heating causes the specimen temperature to change from the preset temperature. The thermal and frictional effects during hot deformation can clearly be seen in the work of Peng et al. [7]. In principle, constitutive analysis requires isothermal stress–strain data. In our opinion the results obtained from hot-working tests at strain rates higher than $10\ s^{-1}$ are not suitable for immediate constitutive analysis unless (adiabatic) temperature changes during high-strain rate deformation are accounted for in the constitutive analysis.

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In the present research, a DSI Gleeble 3800 thermomechanical simulator was used at strain rates up to $100\ s^{-1}$ for a constitutive analysis that takes thermal effects into account. The aim was to evaluate the effect of stress–strain data correction on the accuracy of constitutive constants and the reliability of the flow stresses calculated from the constitutive equation.

Constitutive equations are commonly used to calculate the flow stresses of a material during deformation. Each of the equations developed has an optimum range of strain rates for calculating flow stresses. For creep, the power law is preferred, but it cannot be used when stresses are high. The exponential law is suitable for hot-working processes, but it is limited to relatively low temperatures and high-strain rates [11]. From the literature, it has been found [2,12–15] that the sine hyperbolic description for the Zener–Hollomon parameter can be used for flow stress calculation in the hot-working regime. The sine hyperbolic law combines the power law and the exponential law in, respectively, the low and high stress limit, resulting in a single expression suitable for analysis over the range of temperatures and strain rates currently applied. For the present constitutive analysis of the hot deformation behaviour of a wrought magnesium alloy, the following sine hyperbolic equation was used:

$$Z = A_\varepsilon[\sinh \alpha\sigma]^n = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right). \qquad (1)$$

In Eq. (1), the flow stress σ is related to both the absolute temperature T during deformation and to strain rate $\dot{\varepsilon}$. The material parameters α and n are the stress multiplier and stress exponent, respectively. The variation of flow stress with strain [16,17] was incorporated into a strain-dependent parameter $A_\varepsilon = f(\varepsilon)$.

The as-cast Mg–Al4–Zn1 alloy, the composition of which is given in Table 1, was extruded at a reduction ratio of 10 into a round bar with a diameter of 15.8 mm. Cylindrical specimens, having a diameter of 10 mm and a height of 12 mm, were machined from the extruded bar. The longitudinal axis of the specimens was parallel to the extrusion direction. During machining, the surface of the specimens was kept as smooth as possible in order to exclude any surface effects on the hot deformation behaviour.

Wide ranges of strain rates and temperatures were applied during the hot compression tests using a DSI Gleeble 3800 system. Temperature was varied from 250 to 500 °C in increments of 50 °C. At every temperature, tests were performed at strain rates of 0.01, 0.1, 1, 10 and $100\ s^{-1}$. The specimen was heated at a rate of $10\ °C\ s^{-1}$ and soaked for 60–120 s at the preset temperature in low vacuum to allow the temperature to equalize throughout the specimen. The specimen was then hot compressed at a constant strain rate to a true strain of 1, which resulted in a height reduction from 12 to 4.4 mm. The Gleeble system uses thermocouple feedback to control resistance heating to reach and maintain the preset temperature. A thermocouple was spot welded to the surface of the specimen at the mid-height to measure the actual specimen temperature. To minimize the friction, graphite foils were attached to the water-cooled tungsten carbide anvils using a nickel-containing paste. After the uniaxial deformation, the specimen was air quenched down to room temperature. Three repeat tests at each set of parameters were performed.

Table 1. Composition of the Mg–Al4–Zn1 alloy used in the research

Element	Al	Zn	Mn	Si	Fe	Mg
Wt.%	4.76	0.85	0.32	0.01	0.008	Bal.

The method commonly used for constitutive analysis based on the results obtained from hot uniaxial compression testing has been described previously [16]. In the present work, an attempt was made to advance the method by introducing a strain-dependent parameter of $\ln A$ into the constitutive analysis. The stress–strain data obtained were corrected as described elsewhere [17] for adiabatic heating, load cell ringing and synchronization of force with displacement. The results of the constitutive analysis based on the corrected stress–strain data were compared to the measured stresses.

For comparison purposes, the stress–strain data obtained from the compression tests, both corrected and uncorrected for deformation heating, were used in the constitutive analysis. Because the flow stress curve of the present wrought magnesium alloy displayed a distinct stress peak, it was necessary to perform the constitutive analysis at fixed values of strain.

The constitutive analysis yielded the values of activation energy for deformation Q, stress exponent n, stress multiplier α and material parameter A in Eq. (1), as given in Table 2. The activation energy Q is usually compared to the activation energy of self-diffusion of Mg, which is between 130 and $140\ kJ\ mol^{-1}$ [2,14,18]. The value of $160\ kJ\ mol^{-1}$ obtained for the present alloy is considerably higher than that for AZ61 [16], which is in the range of $131–115\ kJ\ mol^{-1}$. There are no explanations that could be used to account for the high value of activation energy for the present alloy, obtained from the raw stress–strain data. As will be shown later, the overestimated Q value in the constitutive equation will lead to erroneous results of the flow stress.

The adjustable stress multiplier α was found to produce parallel lines in a plot of $\ln[\sinh\alpha\sigma]$ against $\ln\dot{\varepsilon}$ at a value of $0.01\ MPa^{-1}$. This value is comparable to that found earlier for AZ61 [16]. The plots of $\ln Z$ against $\ln[\sinh\alpha\sigma]$ at fixed strains showed that the calculated value of the stress exponent n varied with strain. The linear regression gave an equation of the type $y = Bx + C$, in which B denotes $\ln A_\varepsilon$ and C is equal to the stress exponent n. Instead of displaying a single value, the n value increased from 4.9 at the peak stress to 6.6 at a strain of 0.8.

The most important use of a constitutive equation is to calculate the flow stresses during hot working. The

Table 2. Values of constitutive parameters obtained from both raw and corrected stress–strain data

	α $[MPa^{-1}]$	n	Q $[kJ\ mol^{-1}]$	$\ln A$
Uncorrected	0.01	5–6.6	160	29–32
Corrected	0.01	4.1	130	$1.0078\ln\varepsilon + 25.042$