EXTRUSION LIMITS FOR AZ ALLOYS WITH Al CONTENTS < 3%

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Abstract

An analytical model is developed for the rapid estimation of limiting extrusion speeds. This model is used to analyse the results of a series of laboratory compression extrusion tests. AZ type alloys with Al levels between 0 7% and 3% were used. It was found that lowering the aluminium level increased the maximum extrusion speed by ~4 times. This increase is due mainly to an increase in the cracking limit temperature. The room temperature yield stress decreased by ~60MPa over the same change in Al level. The present model enables the generation of extrusion limit diagrams based on only a few lab extrusion tests.

Introduction

One of the impediments to the uptake of wrought magnesium alloys has been their perceived poor forming characteristics when compared to aluminium. Extrusion speeds for magnesium are typically quoted as between $^2/_3$ and $^1/_3$ that of aluminium [1], with a concomitant reduction in productivity. However, it is also apparent that the extrusion of magnesium alloys and the alloys themselves have not been optimised. With CAFE (Corporate Average Fuel Economy) legislation in the US and EU for fuel economy there is an opportunity for the weight reduction of motor vehicle components which takes advantage of the optimised processing of wrought magnesium. This paper describes a methodology which allows us to evaluate wrought alloys and their processing based on laboratory-scale testing coupled with simulation and modelling.

Extrusion Limit Diagrams

An effective way of comparing the extrudability of different alloys is through the generation of extrusion limit diagrams [1]. A schematic example of such a diagram is shown in Figure 1. Two limit lines form an envelope enclosing a region where extrusion is possible. In the present paper the key concern is extrusion speed, and this parameter is included on the diagram as the mantissa. The initial billet temperature is shown on the abscissa. At low temperatures, the press capacity imposes a limit on the speed that can be reached. At higher temperatures the incipient melting of an alloy phase causes surface cracking. The diagram spans temperatures between 200°C and 600°C but magnesium extrusion is normally carried out at around 400°C. The maximum speed shown is 100mms^{-1}. Speeds higher than this are unlikely to be encountered on typical extrusion presses due the limitation of the press hydraulics.

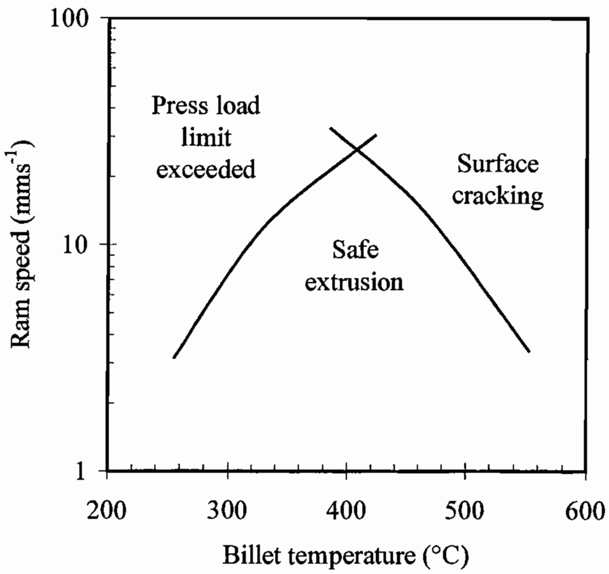

Figure 1. Typical form of an extrusion limit diagram.

To aid in the generation of an extrusion limit diagram it is desirable to develop a mathematical framework that enables prediction of the load and maximum surface temperature. An obvious approach to take is the finite element method but for the sake of calculation time it is more convenient to establish an analytical basis. Such an approach is described below, based on engineering equations readily available in the literature [e.g. 2].

The extrusion pressure is given by:

$$p = \sigma\left(0.17 + 1.86\ln R + \frac{4ml_b}{d_b\sqrt{3}}\right) \qquad 1.$$

where the symbols take the following definitions:

- σ = the mean von Mises effective flow stress
- R = the extrusion reduction ratio
- m = a friction factor (set to unity here)
- l_b = billet length
- d_b = billet diameter

The generation of heat during deformation is approximated using the assumption of adiabatic heating, which gives an upper bound estimate of the temperature rise. The temperature rise is considered in three areas of the extrusion: in main the deformation zone, ΔT_1, at the interface between the container and the billet, ΔT_2, and at the interface between the die land and the extrudate, ΔT_3. These temperatures are estimated using the following expressions (developed by Stuwe [1] as quoted in [2]):

$$\Delta T_1 = \frac{\sigma \ln R}{\rho C_p} \quad \text{2a.}$$

$$\Delta T_2 = \frac{\sigma}{4\sqrt{3}\rho C_p}\sqrt{\frac{v_r l_b \rho C_p}{k}} \quad \text{2b.}$$

$$\Delta T_3 = \frac{\sigma}{4\sqrt{3}\rho C_p}\sqrt{\frac{v_e l_d \rho C_p}{k}} \quad \text{2c.}$$

where the symbols take the following definitions:

ρ = density (1.7 g/cm^3)

C_p = heat capacity (1150 J/kg/K)

v_r = ram speed

k = thermal conductivity (130 W/m/K)

v_e = extrusion speed

l_d = die land length

The stress was calculated using the common hyperbolic sine law, an example of which is given below (modified from an equation derived in [1] for wrought AZ31 tested to a strain of 0.6):

$$\sigma = 90 \sinh^{-1}\left(\dot{\varepsilon} \exp(147000/RT) \big/ 10^{13} \right)^{0.15} \quad \text{3.}$$

where R is the gas constant, T is in Kelvin and the strain rate is given by:

$$\dot{\varepsilon} = \frac{9.6 R^{0.6} v_b}{d_b} \quad \text{4.}$$

Ascertaining the temperature to use in determining the stress in this simple framework is, however, not so straight forward due to the coupling between stress and temperature. An appropriate value of stress was determined by averaging the stress calculated using the initial billet temperature and the stress calculated from the maximum temperature rise predicted assuming the deformation proceeds under the initial stress estimate. This average value of stress is then used to estimate ΔT_1 for use in determining the maximum temperature achieved in the extrusion.

To generate an extrusion limit diagram it is necessary to perform a series of model simulations in which the speed and the temperature are varied. The load and the maximum temperature rise are compared with the maximum allowable values and once the limiting load or surface temperature is exceeded the associated conditions are recorded. These are then plotted to form a limit diagram. In the present work, compression tests are carried out to determine the hot working flow stresses. Laboratory extrusion tests are used to establish cracking limit. The aim is twofold: to verify the usefulness of the approach and to establish the influence of Al level on the extrusion limits of AZ alloys with Al contents below 3%

Experimental Method

Material

Four AZ series alloys were cast with zinc and manganese levels held constant, and nominal aluminium levels of 0.7 wt%, 1.0 wt%, 1.5 wt%, and 2 wt%. Commercially obtained AZ31 was also tested as part of this study.

Compression testing

Uniaxial compression tests were conducted on specimens which were 10 mm in diameter and 15 mm long. The specimens were deformed at true strain rates of 0.1 s^{-1} and 1 s^{-1}, at temperatures of 300°C and 400°C.

Extrusion tests

Extrusion tests (direct extrusion) were carried out on a small scale laboratory rig (Figure 2) designed for use in a 350 kN hydraulic press. The billet dimensions are 30 mm diameter by 20 mm in length. The billet, die and container are heated "in-situ" using electric heating elements. The temperature is measured using a thermocouple inserted into the container through a passage that terminates within ~2 mm of the container wall. For all of the present tests the extrudate was a round bar 5mm in diameter.

The tests were carried out at a constant speed, which was incrementally increased in subsequent tests until surface cracking was observed. An image of a cracked surface is contrasted with a normal finish in Figure 3.

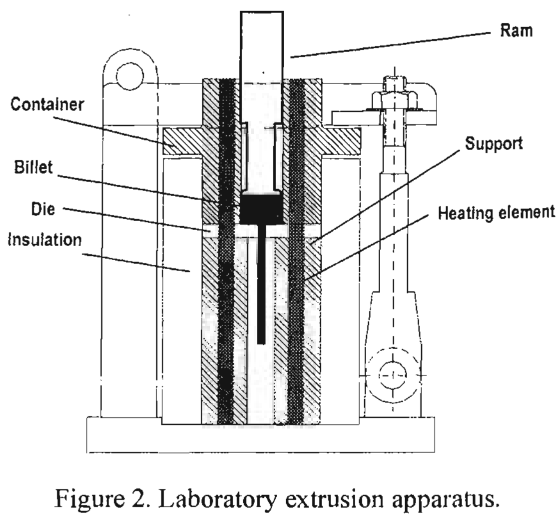

Figure 2. Laboratory extrusion apparatus.

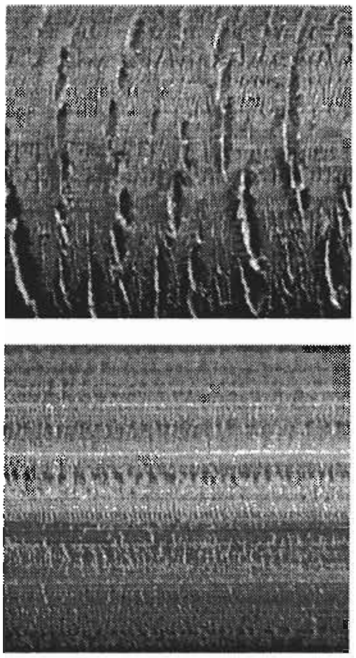

Figure 3. Examples of extrudate surfaces obtained in the present work.

Hot Compression Test Results

A typical series of stress-strain curves obtained using hot compression is presented in Figure 4. The stress increases with increasing strain up to a peak after which work softening takes place at a rate that decreases with strain. This overall trend is common in materials displaying dynamic recrystallization and is typical of magnesium hot worked in compression and torsion [4, 1]. The level of the entire stress strain curve rises with increasing aluminium content, more or less irrespective of the strain. This suggests that aluminium impacts on the deformation stress but does not interfere significantly with the initiation and progress of dynamic recrystallization. For the conditions used in Figure 4, the overall effect of increasing the aluminium level from 0.7% to 3% increases the flow stress by approximately 15MPa (a change of ~25%).

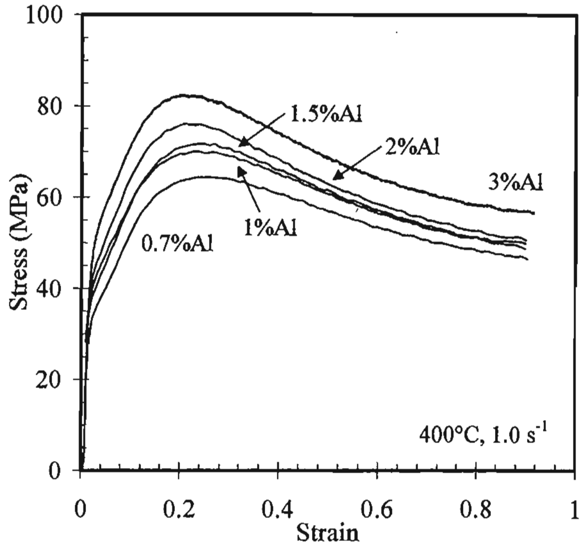

Figure 4. Stress-strain flow curves obtained using hot compression testing.

The flow stress at a strain of ~1, σ_1, is plotted against the temperature corrected strain rate, $Z = \dot{\varepsilon}\exp(147000/RT)$, in Figure 5. Also included in this plot are predictions made using Equation 3 (short dashes), which was developed using compression and torsion tests carried out on fine grained wrought AZ31 [4]. It is clear that the present stresses, established using cast material, fall approximately 10 MPa higher. This difference may be ascribed to the fact that the steady state stress is approached more rapidly in fine grained samples due to the enhanced rate of dynamic recrystallization [1].

It is assumed here that the influence of Al on the hot strength follows the following form:

$$\sigma = \sigma_0 + x\sigma_0[Al] = \sigma_0(1 + x[Al]) \qquad 5.$$

If it is also assumed that the influence of Al is restricted to the pre-hyperbolic sine constant in Equation 3 the following expression can be derived from the present data:

$$\sigma = (85 + 6[Al])\sinh^{-1}\left(\dot{\varepsilon}\exp(147000/RT)\Big/10^{13}\right)^{0.15} \qquad 6.$$

Predictions made using this expression are shown in Figure 5. It can be seen that the influence of Al is accurately reproduced by the model. Due to the coarse grain size and the limited strain employed in the tests, the present data overestimate the steady state stress. The pre-hyperbolic sine term in Equation 6 is therefore adjusted to reconcile it with Equation 3, which is expected to be more representative of the steady state stress. The result is used in the analysis of extrusion that follows and is given by the following expression:

$$\sigma = (72 + 6[Al])\sinh^{-1}\left(\dot{\varepsilon}\exp(147000/RT)\Big/10^{13}\right)^{0.15} \qquad 7.$$

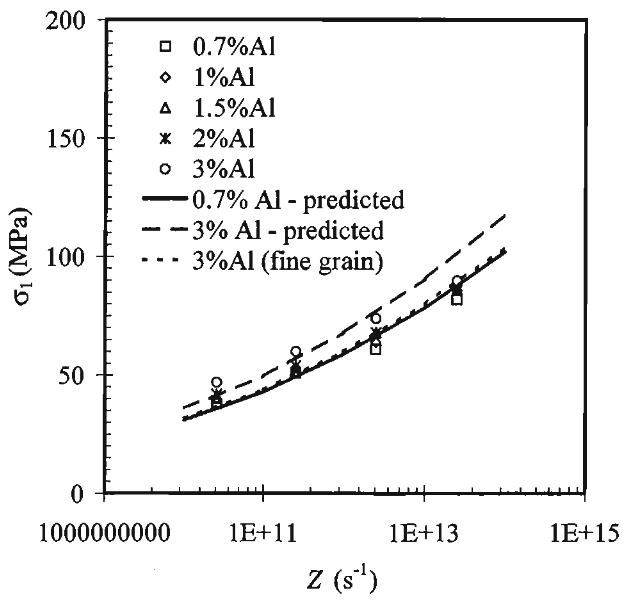

Figure 5. Influence of the temperature corrected strain rate, $Z = \dot{\varepsilon}\exp(147000/RT)$, on the stress at a strain of 1.0.

Lab Extrusion Tests

The extrusion load was recorded in a series of experiments carried out under a range of different temperatures and speeds. The results are compared with predictions made using the approach presented above in Figure 6. It can be seen that despite the many simplifications made, there is reasonable agreement between the model and experiment. The model tends to over-predict the stress at high temperatures (low stresses) and this may be due to the fact that, in most cases, these tests coincided with the occurrence of cracking.

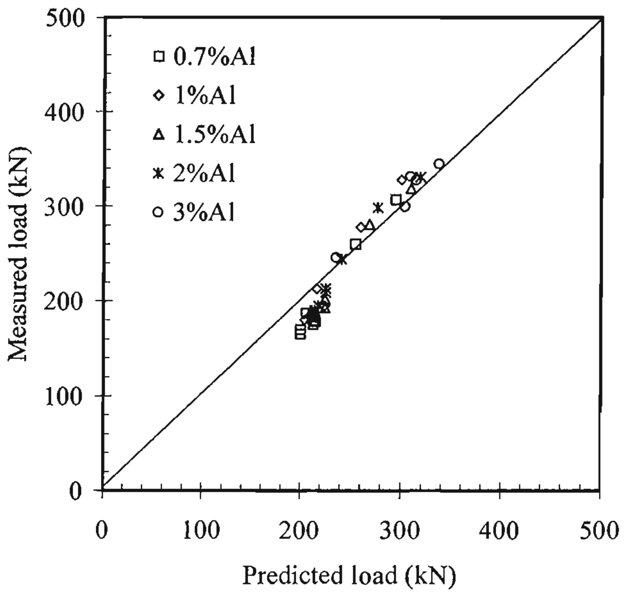

Figure 6. Actual extrusion loads as a function of predicted values.

The lowering of the flow stress that occurs with decreasing Al level allows higher extrusion speeds for a given press capacity. That is, lower Al levels increase the low temperature extrusion limit. The extent of this increase in allowable extrusion speed was ascertained using the present model and the results of the simulations are shown in Figure 7. Despite the moderate influence of Al on the flow stress, a speed increase of four fold is predicted to occur with lowering the Al level from 3% to 0.7%.

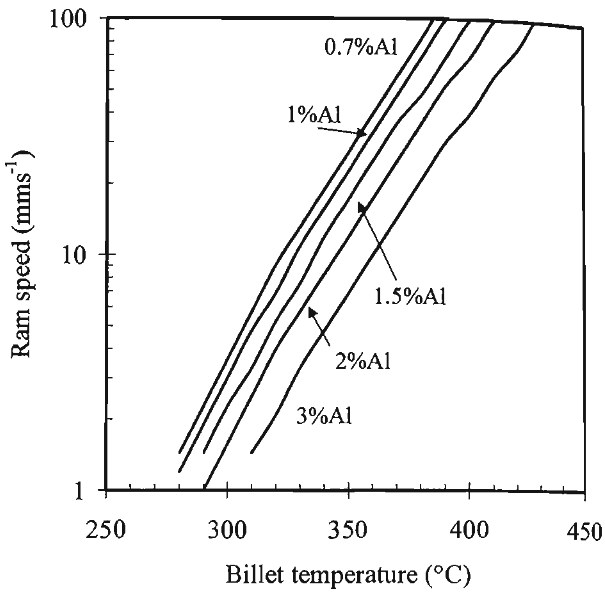

Figure 7. Influence of Al level on the low temperature (press capacity) extrusion limit.

At higher temperatures, incipient melting and associated cracking determines the extrusion limit. To determine the influence of Al on this restriction, tests were carried out on each grade at increasing speed until cracks were observed. The conditions associated with cracking are shown in Figure 8. The lines drawn through the data were fitted using the present model by iterating through different cracking limit temperatures. It is clear that the influence of Al on speed defined by this limit is greater than for the load limit. In this case, increasing the Al content over the range examined raises the speed limit by a factor of between 5 and 10, depending on the temperature.

To illustrate the change in extrusion limit diagram achieved by reducing the Al content from 3% to 1%, both press and cracking limits are plotted in Figure 9. It is predicted that an alloy with 1%Al should be able to be extruded at speeds near to the maximum allowed by the press hydraulics, depending on the safety margin that must be kept between the actual press settings and the limit lines.

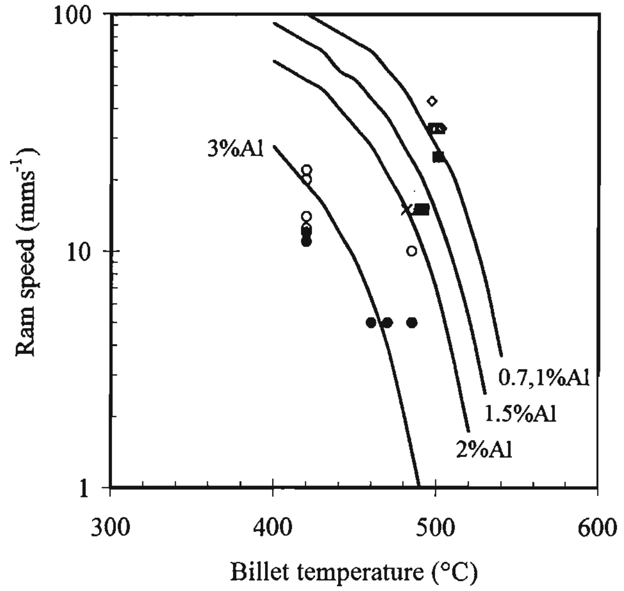

Figure 8. Influence of Al level on the cracking limit. Filled symbols indicate successful extrusion, open symbols indicate cracking.

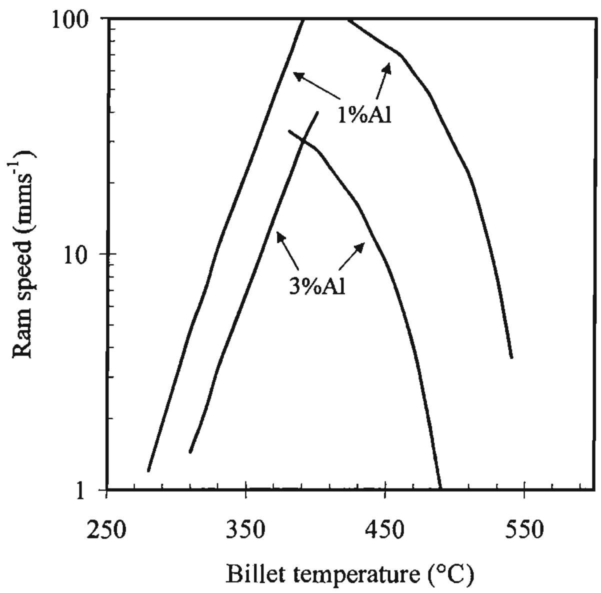

Figure 9. Extrusion limit curves for Al levels of 1% and 3%.

Room Temperature Properties

Lowering the aluminium level decreases the room temperature strength and the magnitude of this effect must be considered in allow design. Tensile proof stresses obtained in the present work are plotted in Figure 10. It is apparent that the "vector" for the influence of aluminium on strength is 25 MPa/%Al. Lowering the aluminium content from 3% to 1% therefore decreases the yield strength by ~50MPa.

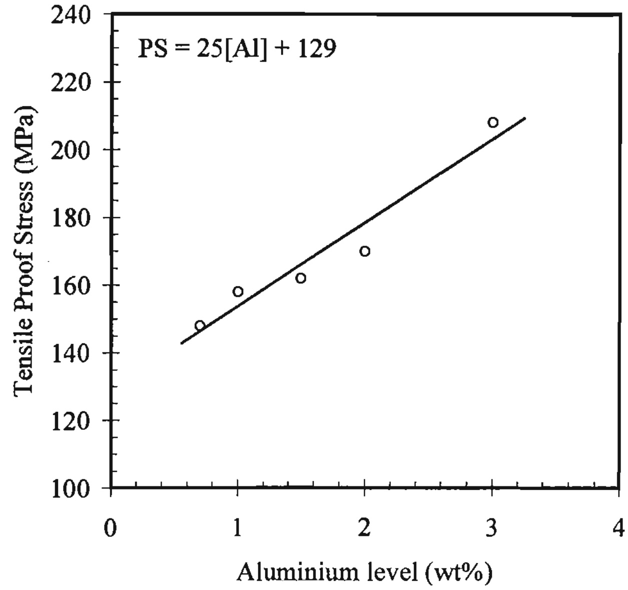

Figure 10. Influence of Al level on the room temperature proof stress measured in tension.

Discussion

Suitability of model for extrusion alloy development

The comparison between predicted and measured extrusion loads in Figure 6 shows reasonable agreement. We can therefore be confident in employing the model to predict the extrusion speed limit at low temperatures (load limit). In the present work, the position of high temperature speed limit (cracking limit) was obtained experimentally. The model provides the shape of the limit curve. However, it should be noted that the assumption of adiabatic heating used in the model is a fairly crude approximation and will lead to increasing errors as the speed is decreased.

Influence of Al levels

For the present extrusion configuration, reducing the Al level from 3% to around 1% increased the maximum possible extrusion speed by 3-5 times. The precise increase achievable depends on how close to the limit it is possible to operate. Although the present work was carried out on a small laboratory press, the speed increases obtained are expected to be the same for commercial scale operations. In this regard it is interesting to note that the maximum speed predicted for the 3% Al alloy (AZ31) is approximately a third to a fifth of the maximum allowable speed, which is the speed at which a typical soft extrusion alloy (e.g. AA6061) would theoretically be able to be extruded. This difference tallies well with anecdotal comments in the literature with respect to the difference in extrusion speeds for the two metals [1].

Conclusions

1) A simple analytical model was able to provide reasonable estimates of the extrusion load.

2) An adiabatic temperature model was "tuned" to provide a fit to experimental cracking limits.

3) Decreasing the Al level from 3% to 1% increases the maximum extrusion speed by a factor of ~4 times but reduces the room temperature yield strength by around 50MPa.

4) The increase in extrusion speed is due mainly to an increase in the cracking limit temperature.

Acknowledgements

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