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Assessment of a physical based modelling suitable to capture the mechanical behaviour at large plastic strain of aluminium alloys

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Abstract. It is reported for the first time the application of a physical-based constitutive law suitable to capture the flow stress and the strain-hardening in a wide range of plastic strain. This law is validated by comparison with experiments related to alloying elements effect and temperature in aluminium alloys especially characterized by bulge test at room and at warm temperature.

Keywords: stress / strain / bulge test / modelling

1 Introduction

Tensile tests usually characterize the mechanical behaviour of materials. This test is limited due to necking occurrence at quite small strain lower than 30%. Unfortunately, there is a strong demand for behaviour laws to describe the behaviour for strains beyond the necking strain, especially for forming operations such as deep-drawing, roll forming, or rolling to predict force etc.

Bulge test set-up as illustrated in Figure 1a, is well known to be suitable for a mechanical characterization beyond the uniaxial tensile strain at necking [1,2]. In bulge test, if the material is assumed isotropic and if the deformation is assumed to be a spherical cap, it comes from Figure 1b [1,2].

The radius of curvature is:

$$R = \frac{H^2 + a^2}{2H} \tag{1}$$

The maximum equivalent strain is:

$$\varepsilon = -2.\ln\left(1 + \frac{H^2}{a^2}\right) = \ln\left(\frac{t}{e_o}\right) \tag{2}$$

And the maximum Von Mises equivalent stress is given as:

$$\sigma = \frac{P \cdot R}{2 \cdot t} \tag{3}$$

Different round robins are available in the literature [3–8] comparing the prediction of mainly Hollomon [8], Swift [9], and Voce [10] laws respectively expressed as:

$$\sigma = K_H \cdot \varepsilon^{n_H} \tag{4}$$

$$\sigma = K_S \cdot (\varepsilon + \varepsilon_o)^{n_S} \tag{5}$$

$$\sigma = \sigma_O + K_V\left(1 - \exp\left(-\frac{\varepsilon}{\varepsilon_H}\right)\right) \tag{6}$$

where σ and ε are respectively the Von-Mises equivalent stress and the Von-Mises equivalent plastic strain. The others parameters are fitting constants.

We can notice that Kocks-Mecking has obtained the Voce law by physical arguments [11]. In this publication, the Voce law is now referred to as KM.

It has been concluded that none of these laws are suitable to capture the evolution of flow stress as a function of strain in a wide range of plastic strains. On the contrary, a new physical based behaviour law has been recently proposed [12] and is given by:

$$\sigma = \sigma_O + \sigma_s \cdot \ln\left(1 + \frac{\theta_O}{\sigma_s} \cdot \varepsilon\right) \tag{7}$$

seems to be promising for this issue where σ_o, θ_o, and σ_s are three parameters to be identified. θ_o controls the initial work-hardening (stage 2) and σ_s controls the saturation of the stress-strain relationship.

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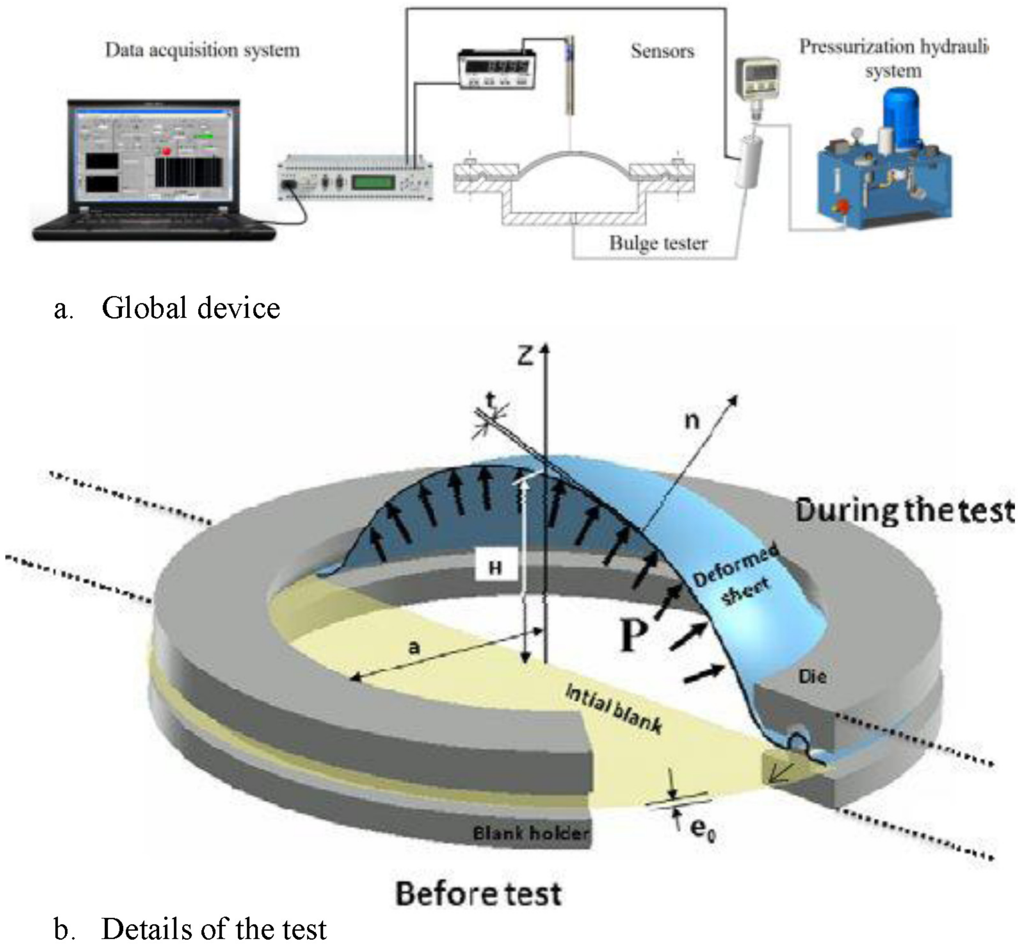

Fig. 1. Principle of bulge test.

2 Experiments and modelling

At first, the new approach has been compared to K-M law concerning the evolution of flow stress in plane stress [12]. It is highlighted in [12] that the two approaches give similar results for low flow stress, but the new one avoids a rapid saturation of strain-hardening for higher stresses which is more consistent with all the available experimental data.

In order to go further, experimental data related to the alloying element (Magnesium) have been selected, especially because they are available in a wide range of plastic strain because obtained by bulge-test used in pioneering work developed in Alcan Research Center [13]. The presented data have already been showed in oral presentation about twenty years ago but they have never been published. All the aluminium alloys have been cast, rolled and heat-treated and quenched Alcan Research Center in order to have the elements in solid solution. Figure 2 shows the agreement between experiments and modelling whatever the plastic strain. The identification of the parameters is reported in Table 1 and plotted in Figure 3. The results highlight that the solute content increases the strain-hardening in stage 2 before saturation, and it regularly increases the stress σ_s.

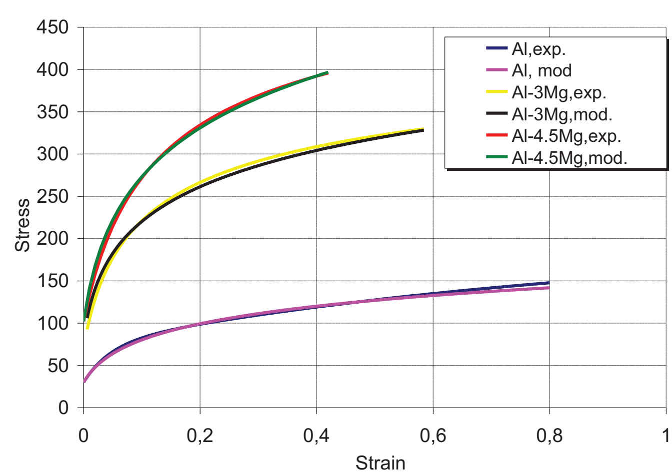

Fig. 2. Comparison between experimental and predicted stress-strain curves in bulge test for different Al-Mg alloys.

As shown in Figure 4, the temperature exhibits a strong effect on flow stress during a bulge test. The proposed approach is suitable to capture this effect with a constant value of strain-hardening in stage 2 but with an increase in the critical stress σ_s, i.e. the dynamic recovery as reported in Table 2.

Table 1. Identified values of the parameters of the modelling as a function of solute content.

	σ_o (MPa)	θ_o (MPa)	σ_s (MPa)
Pure Al	30	1180	33
Al-3Mg	82	4800	65
Al-4.5Mg	102	4800	95

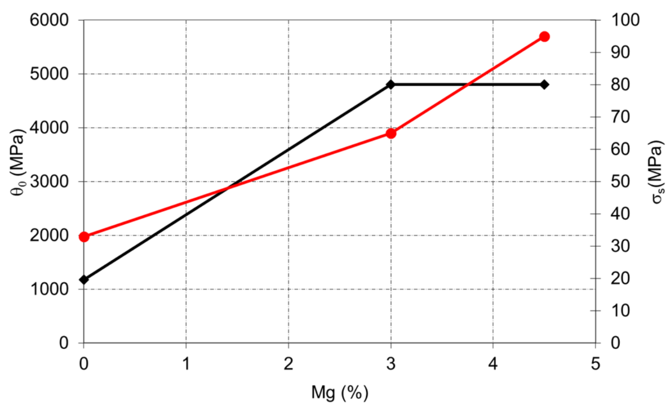

Fig. 3. Evolution of the parameters as a function of magnesium content (dots for θ_o and diamonds for σ_s).

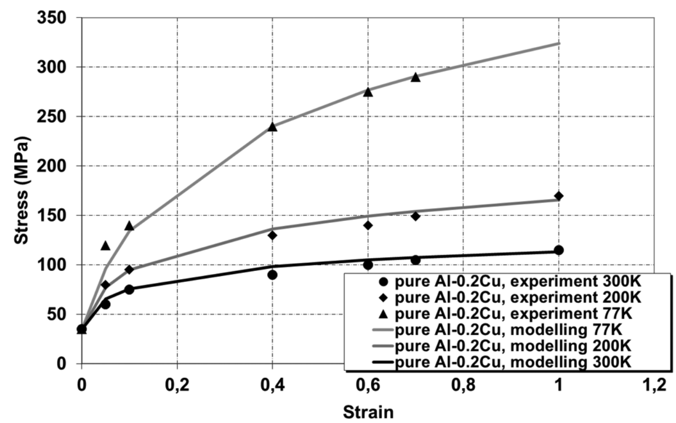

Fig. 4. Assessment of the modelling as a function of temperature for Al-0.2%Cu alloy during a bulge test.

Table 2. Identified values of the parameters of the modelling as a function of the temperature.

Temperature (K)	σ_o (MPa)	θ_o (MPa)	σ_s (MPa)
300	35	1700	15
200	35	1700	33
77	35	1700	100

3 Conclusions

A physical behaviour law has been assessed with a very limited number of constants. For the first time, this law has been validated in a wide range of plastic strains considering solutes and temperature in aluminium alloys using data provided by bulge test.

The avenues are numerous:
– Prediction of Yield Stress, Ultimate Tensile Strength and Uniform Elongation in tension.
– Application of this law to other metallic materials.
– Easy implementation in Finite Element Code for forming simulations.
– Include the strain rate effect.

Competing interests

The authors declare that they have no conflict of interest.

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