Experimental characterisation and modelling of deformation-induced microstructure in an A6061 aluminium alloy

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Abstract. For industry, the mechanical properties of a material in form of flow curves are essential input data for finite element simulations. Current practice is to obtain flow curves experimentally and to apply fitting procedures to obtain constitutive equations that describe the material response to external loading as a function of temperature and strain rate. Unfortunately, the experimental procedure for characterizing flow curves is complex and expensive, which is why the prediction of flow-curves by computer modelling becomes increasingly important. In the present work, we introduce a state parameter based model that is capable of predicting the flow curves of an A6061 aluminium alloy in different heat-treatment conditions. The model is implemented in the thermo-kinetic software package MatCalc and takes into account precipitation kinetics, subgrain formation, dynamic recovery by spontaneous annihilation and dislocation climb. To validate the simulation results, a series of compression tests is performed on the thermo-mechanical simulator Gleeble 1500.

1. Introduction

Plastic forming behavior can be divided into different stages. A stage is defined by a change in the dominant microstructural mechanism leading to a characteristic stress-strain relation. For polycrystalline materials, mainly stages III and IV (eventually stage V) are relevant [1] [2]. The stress response of a material caused by external loading is closely related to the mean free path (MFP) for dislocations [3]. This MFP is influenced by obstacles. Dominant obstacles define the dominant hardening mechanism. As dislocations work as dominant obstacles for low strains, the overall dislocation density and its evolution over strain $\rho(\varepsilon(t))$ (i.e. over time for constant strain rate) is a convenient model state parameter. This is the case in stage III. In order to reduce their total energy, dislocations tend to agglomerate to a honeycomb like structure. The mechanism of subgrain formation [4] becomes dominant in stage IV. A model that describes stages III and IV, therefore, needs two state parameters, one for the evolution of the dislocation density and one for subgrain formation. In this paper, the dislocation density inside subgrains $\rho_i$ and the dislocation density stored in subgrains walls $\rho_w$ are used as state-parameters. The following evolution equations are used in this paper, see also refs. [5] [6].

$$\sigma = \sigma_o + \sigma_r + \sigma_v = \sigma_o + \alpha M b \mu \sqrt{\rho} + \alpha M b \mu \sqrt{\rho_w}$$

(1)
\[
\frac{d\rho}{d\varepsilon} = \frac{M}{bA} \sqrt{\rho} - \frac{Bd}{b} \rho, \quad (2)
\]

\[
\frac{d\rho}{d\varepsilon} = \frac{M}{bD} \sqrt{\rho}, \quad (3)
\]

where \(\alpha\) is a constant, \(M\) is the Taylor factor, \(b\) is Burgers vector, \(\mu\) is the shear modulus, \(d_{\text{crit}}\) is a critical distance for spontaneous dislocation annihilation [7], \(\nu\) is Poisson’s ratio and \(A\), \(B\) and \(D\) are hardening parameters. \(\sigma_0\) is the yield stress. Eq. (1) describes the link between dislocation density and stress response and was first suggested by Taylor [8]. Eq. (2) and Eq. (3) are equivalent to the evolution equations defined in the Kocks-Mecking-model (KM-model) [9]. For a derivation of this model, see ref. [6].

2. Parameters A, B and D

Eqs. (1-3) present a convenient physical model that is capable of describing the main influences on flow curve behaviour. Parameter \(A\) is related to dislocation storage, parameter \(B\) to dislocation annihilation and parameter \(D\) is related to relaxation processes due to subgrain formation. These mechanisms combined with yield stress define the deformation behaviour of a material. Parameters \(A\), \(B\) and \(D\) fully characterize the hardening characteristics of a material under static loading conditions, where \(A\), \(B\) and \(D\) must be expressed in relation to temperature, strain rate and the microstructural state. For further reading, see e.g. ref. [10]. The aim of this paper is to describe \(A\), \(B\) and \(D\) based on comprehensive experimental testing. That means to derive these values for experimental flow curves in different heat treatment conditions, temperatures and strain rates as a basis for further physical modelling. Especially, the relation between yield stress and the storage and annihilation terms is closely investigated.

The relations between hardening parameters and the shape of a stress strain curve are the following. Parameter \(A\) is indirectly correlated with the initial hardening rate \((d\sigma/d\varepsilon)\) that is the angle between the stress-strain curve and the strain-axis. A low value of \(A\) corresponds to a high hardening rate after yielding. Together with parameter \(B\), the curvature in stage III and its saturation stress are defined. The saturation stress remains constant, if the product of \(A\) and \(B\) are constant [6]. A lower saturation stress correlates to a lower saturation dislocation density. Parameter \(D\) is a measure for the hardening rate in stage IV. A high \(D\) parameter correlates to a low hardening rate in stage IV.

3. Experiments and modelling

Experiments are carried out on a Gleeble 1500 Thermo-Mechanical Simulator. Cylindrical specimens, made from an A6061 aluminium alloy, are used in the dimensions of 15x10mm. The chemical composition is summarized in Table 1.

| Element | Al | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti |
|---------|----|----|----|----|----|----|----|----|----|
| Concentration [wt %] | 97.35 | 0.69 | <=0.7 | 0.23 | 0.11 | 0.85 | 0.18 | <=0.25 | <=0.15 |

The specimens are solution heat treated for 1h at 540°C, water quenched and aged at 170°C (artificial ageing). This procedure follows the suggestions of the norm EN 2700 [11]. The ageing time is varied between 1h, 5h, 10h and 96h, with all tests performed twice. Mo foils are used for friction control and as separation between the specimen and the W stamps. The stress is calculated under the assumption of constant specimen volume and no barrelling. Table 2 summarizes the parameters used in the calculations.
Table 2. Constants used in modelling

| Abbr. | Name                        | Value   | Unit |
|-------|-----------------------------|---------|------|
| b     | Burger’s vector             | $2.84 \times 10^{-10}$ | [m]  |
| M     | Taylor factor               | 3.06    | [-]  |
| G     | Shear modulus               | $2.6 \times 10^{10}$  | [Pa] |
| ν     | Poisson’s ratio             | 0.3     | [-]  |
| $Q^v$ | Vacancy formation energy    | 0.67    | eV   |
| α     | Strengthening coefficient   | 0.5     | [-]  |

The coefficients $A$, $B$ for inner dislocation density and $D$ for dislocation density in subgrain walls are calculated based on Eqs. (1), (2) and (3).

4. Results

4.1 Temperature and strain rate behaviour.

Figure 1 shows the true stress over true strain behavior for 5h of ageing time. Figure 2 shows the corresponding hardening rate ($d\varepsilon/d\sigma$) for stage III over true stress $\sigma$ in a Kocks-plot. The following characteristics can be observed:

- higher yield strength for lower temperature and higher strain-rates (i.e. no negative strain rate sensitivity in that temperature and strain rate range). Interestingly, the slopes of the curves for both temperatures in stage IV are lower for higher strain-rates.

- The hardening rate at the yield point (y-intercept in Figure 2) is higher for lower temperatures.

- The lines in the Kocks-plot are steeper for higher temperatures and lower strain-rates (less pronounced for 25°C). That means that the stress-strain curves decrease faster into stage IV.

**Figure 1.** shows the true stress over true strain behaviour for different temperatures and strain rates for 5h of artificial ageing at 170°C. **Figure 2.** shows the hardening behaviour for the curves shown in Figure 1.
4.2 Hardening parameters

Figure 3 and Figure 4 show the parameters A, B and D for different ageing times and strain-rates over the yield stress. The values of the parameters vary between 35 and 65 for A, between 3 and 7 for B parameters and between 3 and 6 for D. Obviously there is a tendency for hardening parameters to increase with increasing yield strength. For the shape of the flow-curve, this means that a high yield strength leads to a lower initial hardening rate and lower hardening in stage IV, i.e. the curves are flatter.

![Figure 3](image1)

*Figure 3.* shows the A and B values for 25°C, two different strain rates and different ageing times.

![Figure 4](image2)

*Figure 4.* shows the D values for 25°C, two different strain rates and different ageing times.

Figure 5 shows the 0.2% proof stress for all tested samples for different strain-rate, temperatures and artificial ageing times.

![Figure 5](image3)

*Figure 5.* 0.2% proof stress for all samples.

Discussion and Conclusion

The deformation behaviour of an A6061 aluminum alloy is investigated experimentally and modelled by a state-parameter-based Kocks-Mecking type approach. The following conclusions are obtained:
A, B and D as defined above are useful parameters to define and compare hardening behaviour of a flow curve.

Strain-rate, temperature and initial microstructure have an influence on yield stress and hardening behaviour. Within the range of artificial ageing at one temperature the testing temperature has the highest influence on yield stress and hardening.

For a good agreement between model and experiment, all three parameters need to be adjusted. The original paper from Kocks [9] on this topic assumes a constant initial hardening rate (i.e. a constant A parameter) for pure metals. Parameter A is related to the obstacle spacing solely defined by dislocation arrangement in pure metals but also influenced by precipitation and solid solution in industrial alloys.

A clear correlation between yield stress and hardening behaviour (Figures 3 and 4.) is observed. It appears that the influence of precipitation, solid solution and grain boundaries on the yield stress and the hardening behaviour are related through dislocation dynamics. A combined observation for further research is therefore recommended.

The presented model is capable of describing microstructure state dependent flow curve data in a comprehensible physical form. Furthermore, in combination with additional physical modelling for the hardening parameters, a predictive modelling of flow curves is achievable.

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