Hot Deformation of Aluminium Alloys

As part of the further development of the mechanical properties capability for JMatPro, a methodology has been developed that allows the high temperature strength and flow stress curves (FSC) of aluminium alloys to be calculated in various heat-treated conditions. This report first briefly introduces the material models developed to perform such calculations, and then gives examples to demonstrate this calculation capability for a series of aluminium alloys over a wide range of testing conditions.

Depending on the formation of precipitates and their potential strengthening contributions, aluminium alloys can be classified in two groups: age-hardenable and non-age-hardenable. This is quite similar to nickel-based superalloys, therefore the high temperature strength of aluminium alloys has been modelled via procedures similar to that of nickel-based superalloys as described in Ref. 1. Two competing mechanisms for deformation, either dominated by dislocation glide (DDG) or dominated by dislocation climb (DDC), were considered in the calculation. Flow stress curve is just another description of material flow under deformation, as such it is governed by the same deformation mechanisms where DDG mode contributes to strain hardening and DDC mode is responsible for flow softening.

The modelling of flow stress curve is essentially the same for most, if not all, metallic systems, and is described in Ref. 2 for titanium alloys. Some relevant information has also been given in an earlier report [3], which describes models corresponding to the calculations of T5 and T6 peak strengths of aluminium alloys. The present model considers coarsening of the hardening precipitates formed after T5 and T6 treatment when held at temperature prior to testing, which can have a very powerful effect on flow stress behaviour. For example, Fig. 1 shows the high temperature strength calculation for aluminium alloys 2024 and 7075, after various exposure times at testing temperatures. The experimental data are taken from Ref. 4.

As can be clearly seen, using the 0.5h curve of alloy 2024 as an example, the deformation mechanism switches from DDG mode to DDC mode at around 120°C, resulting in a sharp drop in the yield strength. The coarsening of the hardening precipitates when held at temperature before testing consequently results in a drop in strength. The experimental data clearly shows such trend, which is also reflected in the calculated flow stress curves. When the combination of exposure time and testing temperature leads to precipitates that are too coarse to have any significant strengthening contribution and/or have dissolved in the matrix, the alloy strength will be controlled by the matrix strength, as shown by the convergence of strength curves as 400°C is approached (Figs. 1(a) & (b)).
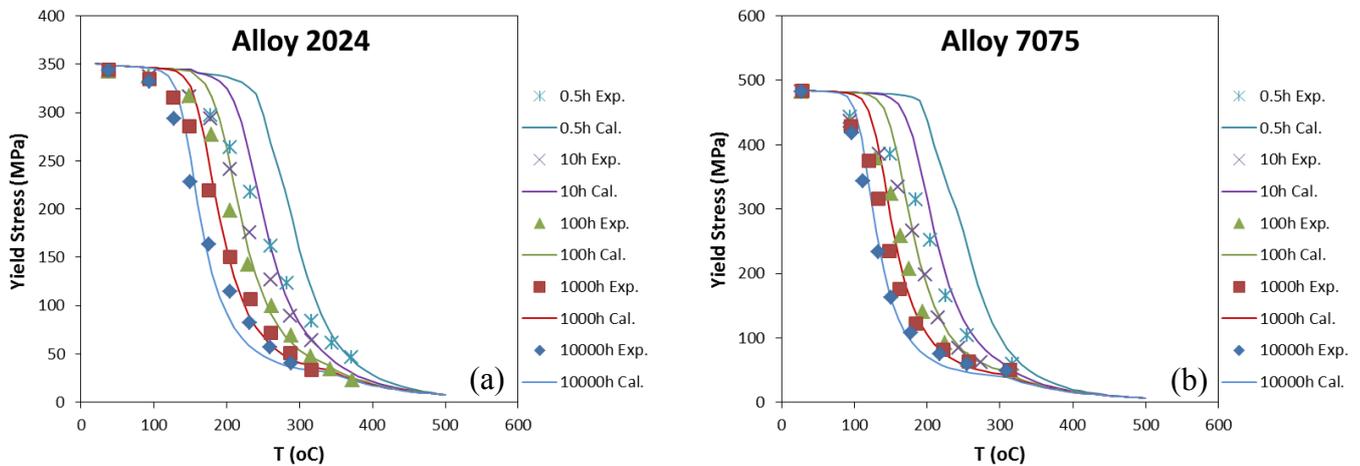
Fig. 1, Calculated high temperature strength for alloys (a) 2024, and (b) 7075 after various exposure times at testing temperatures.

Flow stress curves have been calculated for a variety of alloys and compared with experiment. Some of the alloys used in model assessment are listed in Table 1. Figs. 2 and 3 show the calculated flow stress curves

of two of them over a wide range of testing temperatures and strain rates against experimental data taken from literature. The Al-Cu-Mg alloy in Fig. 2 is in naturally aged (T4) condition. As Ref. 5 does not quote the yield strength of this T4-treated alloy, the yield strength of alloy 2024 in T4 condition, i.e. 325 MPa, is used in the calculation. The 7075 alloy in Fig. 3 is in as-cast form. It is assumed to be from high pressure die casting in the calculation.

Table 1, Alloy information and experimental data source.

Alloy name	Alloy composition (wt%)	Prior condition	Calculation settings	Reference
2xxx (18)	Al-4.95Cu-1.45Mg-0.63Mn-0.11Fe-0.05Zn-0.02Ti-0.12Si	Solution treatment + natural aged	T6 (25°C) RTYS: 325 MPa	Ref. 5 (Fig. 2)
3003 (14)	Al-0.6Si-0.7Fe-0.125Cu-1.25Mn-0.25Zn	Not available	O (500°C) RTYS: 125 MPa	Ref. 6
4343 (24)	Al-7.5Si-0.8Fe-0.25Cu-0.1Mn-0.2Zn	Not available	O (500°C) RTYS: 124 MPa	Ref. 7
5xxx (3)	Al-2.36Mg-2.33Cu-1.12Ni-1.04Fe-0.16Si	Cold reduction + 500°C anneal	O (500°C) RTYS: calculated	Ref. 8
6061 (12)	Al-1.2Mg-0.9Si-0.6Cu	Cast + H (550°C) + water quench	O (550°C) RTYS: calculated	Ref. 9
7075 (1)	Al-5.50Zn-2.23Mg-1.74Cu-0.26Cr	Homogenised	O (465°C) RTYS: calculated	Ref. 10
7150 (2)	Al-6.44Zn-2.47Mg-2.29Cu-0.16Si-0.15Fe	Cast + H (465°C)	O (465°C) RTYS: calculated	Ref. 11
7075 (5)	Al-5.5Zn-2.2Mg-2.2Cr-1.7Cu-0.4Si-0.3Fe-0.1Mn	As-cast	F – Die casting	Ref. 12 (Fig. 3)

Note: H – homogenised, RTYS – room temperature yield strength.
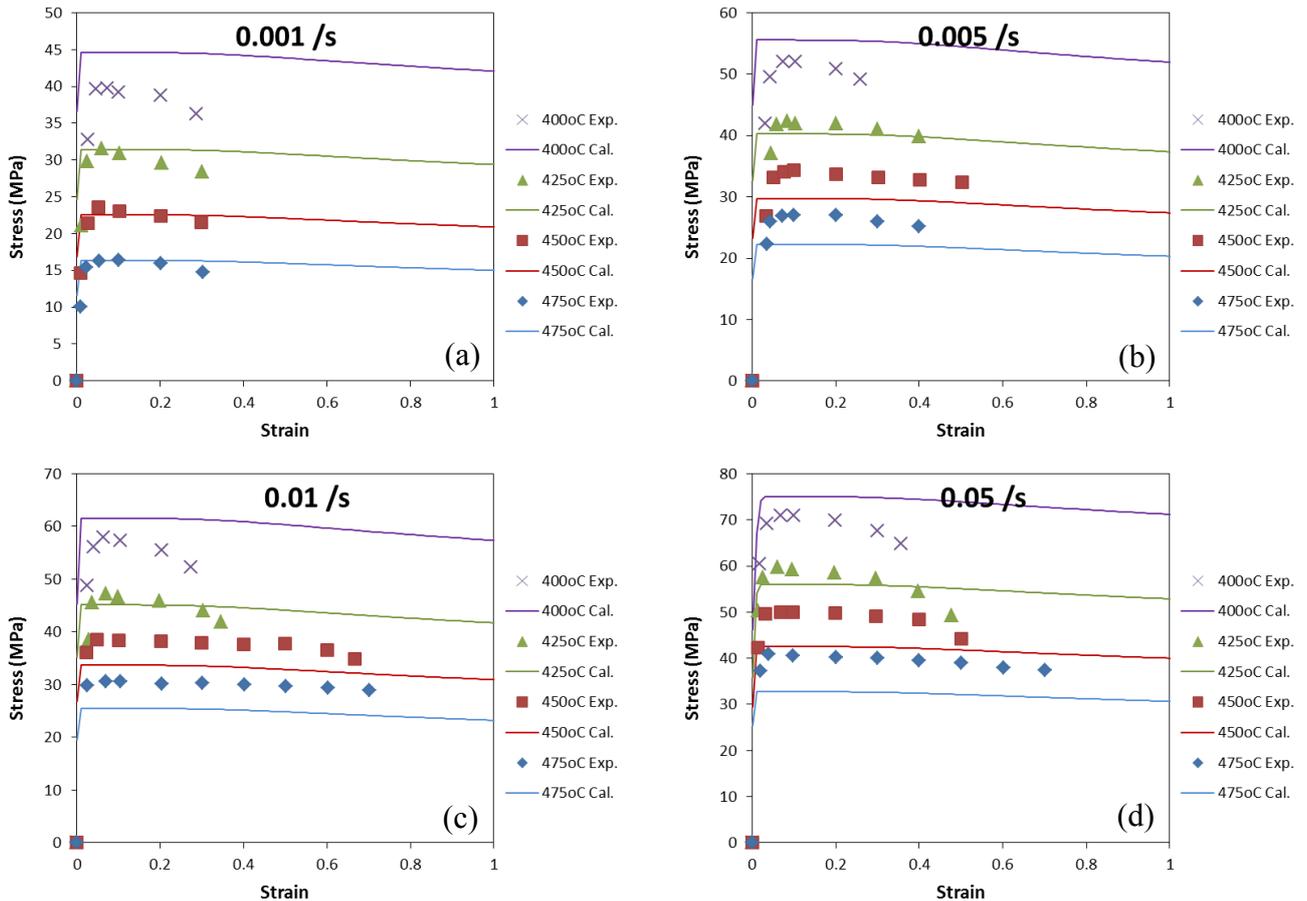
Fig. 2, Calculated flow stress curves of an Al-Cu-Mg alloy over a range of temperatures and strain rates.
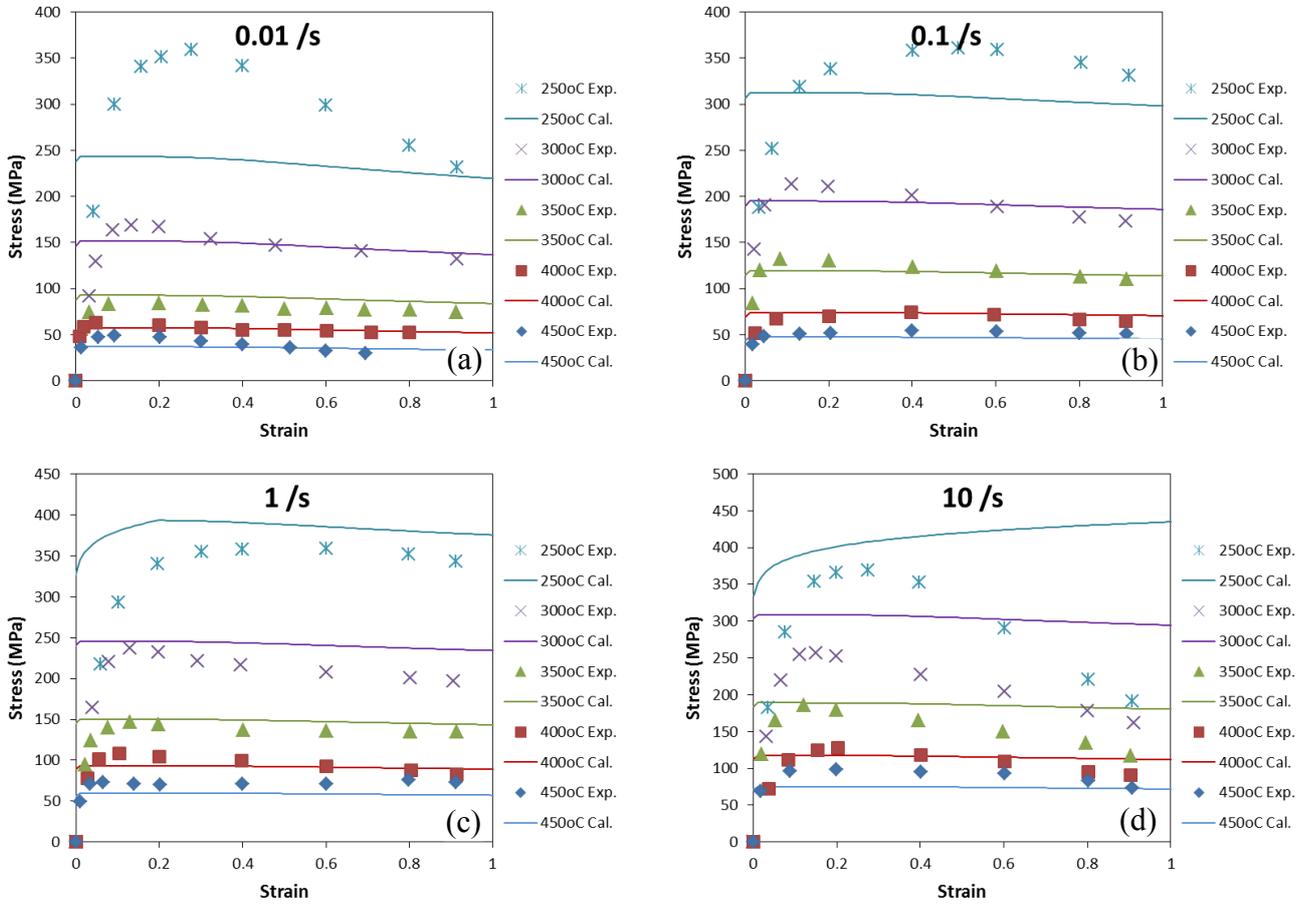
Fig. 3, Calculated flow stress curves of a casting 7075 alloy over a range of temperatures and strain rates.

While Figs. 2 and 3 provided direct comparison of flow stress curves, it is more instructive to look at the overall accuracy of flow stress calculations. Fig. 4. compares the calculated and experimental flow stress taken at various strains between 0.1 and 0.5 over a wide range of temperatures and strain rates for all the alloys listed in Table 1.
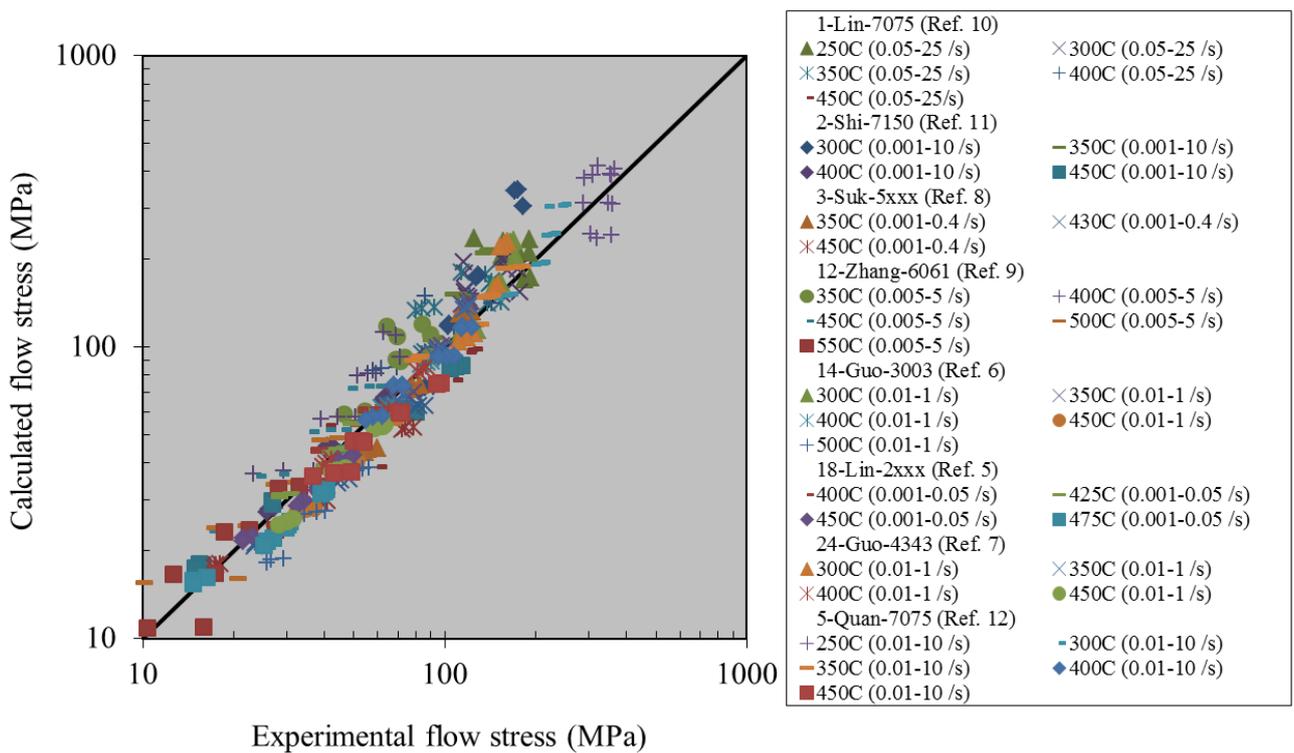
Fig. 4, Comparison between calculated and experimental flow stress data for a number of alloys.

The prior conditions of alloys 3003 and 4343 are not reported. But, as they are not age-hardenable alloys, they are usually used in cold worked condition. Therefore user-input yield strength of 125 MPa (alloy 3003 in H12 condition) or 124 MPa (alloy 4343 in wire form) is used in the calculation. The exact state of the alloys used in Refs. 8-11 is less clear, but they were all cooled down from high temperatures to room temperature before testing. As such, some precipitation may have occurred (i) during cooling, (ii) during holding before testing, or (iii) even during testing. Their exact condition cannot be currently modelled as the present models only consider the transformation and coarsening of precipitates formed in the T5 and T6 conditions. Bearing this in mind, the agreement shown in Fig. 4 is quite good.

Generally speaking, good agreement has been achieved at higher temperatures above 350°C in the current approach. But below this, flow stress curves can be higher than observed in the alloys studied here. As such, further research work will be undertaken to improve the model performance at these mid range temperatures e.g. between 200-350°C.

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