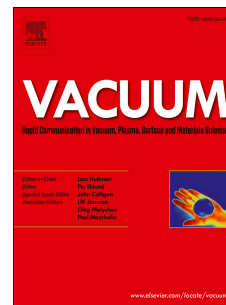


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## Effect of alloy composition on hot deformation behavior of some Al-Mg-Si alloys

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### ABSTRACT

The hot flow stress behavior of three Al-Mg-Si alloys was determined by performing hot deformation compression tests on a Gleeble 3500 thermomechanical simulator over the temperature range 400 °C to 550 °C and at strain rates from 0.01 s<sup>-1</sup> to 10 s<sup>-1</sup>. Using the hyperbolic sine constitutive model, constitutive parameters for prediction of the hot flow stress behavior of these different alloys were determined. The effect of chromium (Cr) addition and increased Mg-Si content on the average steady flow stress, constitutive and strain rate sensitivity (m) parameters was determined. For deformation at low strain rates (0.01-1 s<sup>-1</sup>), the alloy containing 0.2 wt % Cr exhibited higher average steady flow stress than the alloy with similar Mg-Si content and no Cr addition. The addition of 0.2 wt % Cr and an increase in Mg-Si content were observed to result in a decrease of the strain rate sensitivity parameter (m) and an increase in the activation energy for hot deformation. The predictive accuracy of the developed models was demonstrated by comparing the predicted and experimental flow stress behavior of alloy 3 at deformation conditions different from the temperature and strain rate conditions used to develop the models parameters. Results indicate that the developed model can accurately predict the alloy behavior at strain rate and temperature conditions beyond the range of model development.

Keywords: Al-Mg-Si alloys, hot deformation compression, hyperbolic sine equation, activation energy, strain rate sensitivity parameter, Cr addition

### 1. Introduction

Al-Mg-Si alloys are heat treatable aluminum alloys that contain Mg and Si as major alloying elements. Due to their high strength to weight ratio, good corrosion resistance and thermal conductivity as well as excellent extrudability; Al-Mg-Si alloys find vast application in both the automotive and architectural industries [1]. Knowledge of the hot deformation flow stress behavior of Al-Mg-Si alloys is important in order to effectively model forming processes such as extrusion and hot rolling. Liao et al. [2] reported that an increase in the Si content from 0.6 to 12.3 wt % in an Al-Mg-Si alloy results into an increase in the alloy's steady state flow stress and deformation activation energy due to increased presence of silicon particles that

impede dislocation movements. Odoh et al. [3] reported that an increase in the Mg and Si solute content with increasing hold time results into an increase in AA6063 flow stress during hot deformation compression by increasing the alloy's deformation resistance. Ali et al. [4] developed a modified crystal plasticity framework for simulating the hot deformation compression of AA6063 aluminum alloy. The predicted texture and grain size at various deformation conditions were observed to correlate well with microstructures obtained in an optical microscopy examination of deformed samples. Nes et al. [5] reported that Mn and Si additions have a significant effect on the hot deformation flow stress behavior of AA6060 and AA6082. These alloys were observed to have significantly higher hot deformation activation energy in comparison with binary alloys such as Al0.5Si and Al1Si. Complex solute atom interactions were observed between Mg-atoms on the one hand and Mn-and Si-atoms on the other. These interactions were reported to be ultimately responsible for the higher hot deformation activation energy of the Al-Mg-Si alloys. Baxter et al. [6] reported an increase in the flow stress and activation energy for hot deformation of Al-Mg alloys with increasing Mg content. The increase in average flow stress and activation energy was reported to be due to an increase in Mg solute atoms serving as obstacles to dislocation movement. During hot deformation compression of an Al-Si alloy, Wang et al. [7] reported an increase in the hot deformation activation energy of the alloy from 152 kJ/mol to 180 kJ/mol when the Si content is increased from 2 to 15 wt %. This increase was attributed to the role of Si solute atoms that serve as obstacles to dislocation movement. The lower diffusivity of Mn in aluminum in comparison to aluminum self-diffusion has been reported to be responsible for the increase in activation energy for hot deformation ( $Q$ ) in an Al-Fe-Si alloy with 0.2 wt % Mn [8]. The addition of 0.2 wt % Mn was reported to result into an increase in flow stress, retardation of the dynamic recovery process and activation energy increase from 161 kJ/mol to 181 kJ/mol. Shaha et al. [9] reported an increase in the flow stress and activation energy of an Al-Si-Mg alloy with V and Zr additions due to formation of thermally stable  $Al_3V$  and  $Al_3Zr$  precipitates during the hot deformation process. These precipitates were observed to exert increased strengthening effect by serving as barriers to dislocation movement. The activation energy of the base Al-Si-Mg alloy and Al-Si-Mg-0.2Zr-0.25V were 283 kJ/mol and 315 kJ/mol respectively. Despite efforts invested in understanding the hot deformation behavior of Al-Mg-Si alloys, there exists limited knowledge on the systematic effect of Cr and Mg-Si on the hot flow stress behavior, strain rate sensitivity

and deformation activation energy of these alloys during hot compression deformation. Previously developed models available in the literature for predicting the flow stress behavior of aluminum alloys have only been validated within the range of test deformation conditions [3, 7].

In this research, the influence of an increase in Mg-Si content and the addition of 0.2 wt % Cr on the hot flow stress behavior, strain rate sensitivity and activation energy of commercially relevant Al-Mg-Si alloys have been determined. Using hyperbolic sine relationship, models were developed for predicting the flow stress behavior of these alloys. These models were validated by determining their predictive accuracy within and beyond the range of test deformation conditions.

## 2. Materials and Method

The Al-Mg-Si alloys studied in this work were direct chill (DC) cast into billets and homogenized at 560 °C (100 °C/h) for 4 hours followed by air cooling. Cylindrical compression samples with nominal dimensions  $\varnothing 10 \text{ mm} \times 15 \text{ mm}$  were machined out at the centre location of homogenized billets. The chemical composition of the alloys is given in Table 1.

Table 1: Chemical composition (in wt %) of tested Al-Mg-Si alloys

| Alloy | Si  | Fe   | Cu   | Mn  | Mg   | Ti | Cr  | Al      |
|-------|-----|------|------|-----|------|----|-----|---------|
| 1     | 0.5 | 0.20 | 0.15 | 0.1 | 0.50 | -  | 0.2 |         |
| 2     | 0.6 | 0.20 | 0.15 | 0.1 | 0.90 | -  | -   | Balance |
| 3     | 0.6 | 0.20 | 0.15 | 0.1 | 0.90 | -  | 0.2 |         |

The homogenized microstructures for the aluminum alloys in this work are shown in Figure 1.

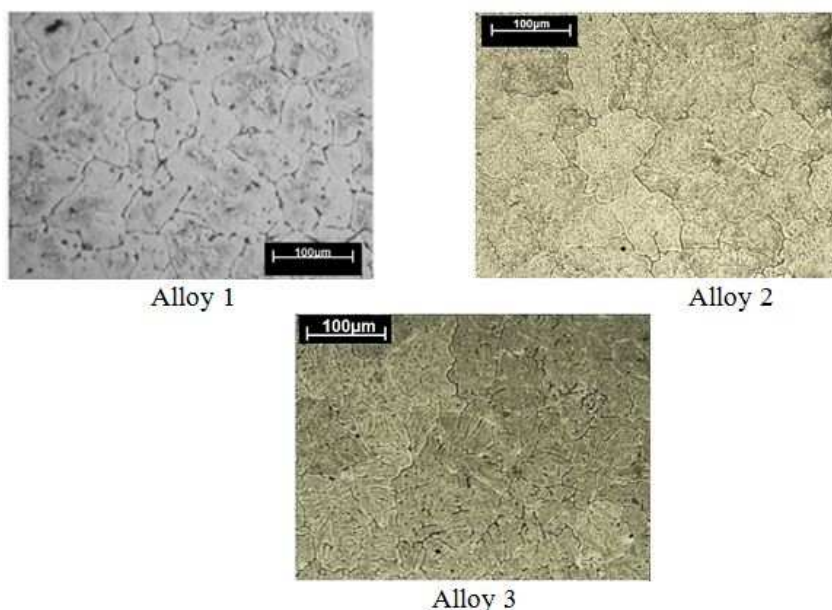


Figure 1: Homogenized microstructures

The homogenized microstructures of the alloys were observed to exhibit an equiaxed grain structure. The presence of platelet like AlFeSi phases at interdendritic regions as well as Mg<sub>2</sub>Si particles in the Al-Mg-Si alloys was confirmed by electron dispersive spectroscopy (EDS). In alloys 1 and 3 containing 0.2 wt % Cr, small Al(Cr)Fe particles were observed to nucleate on the surface of the AlFeSi phases. The presence of small  $\alpha$ -Al(CrFe)Si particles in Al-Mg-Si alloys with < 0.3 wt % Cr content has also been previously reported [10].

The hot deformation compression tests were performed at deformation conditions of 400 °C, 450 °C, 500 °C and 550 °C and strain rates of 0.01 s<sup>-1</sup>, 0.1 s<sup>-1</sup>, 1 s<sup>-1</sup> and 10 s<sup>-1</sup> in a Gleeble 3500 thermo-mechanical simulator at the University of Waterloo. Samples were heated at 10 °C/s to the deformation temperature and held for 60 seconds prior to deformation to ensure homogenous temperature distribution within the sample. The samples were then deformed to a true strain of 0.6 followed by water quenching in order to retain the post-deformation microstructure. Experiments were repeated three times for each deformation condition in order to check for consistency and repeatability of the measured flow stress data. The constitutive models for predicting the hot deformation flow stress behavior of the Al-Mg-Si alloys were thereafter developed using the Sellars-Tegart hyperbolic sine relation [11] and data obtained from the stress-strain curves for the identified deformation conditions. Hot deformation compression of alloy 3 was performed at 20s<sup>-1</sup> (500 °C) in order to verify the capability of the developed models in predicting the flow stress behavior of these alloys at strain rates beyond the range of model development.

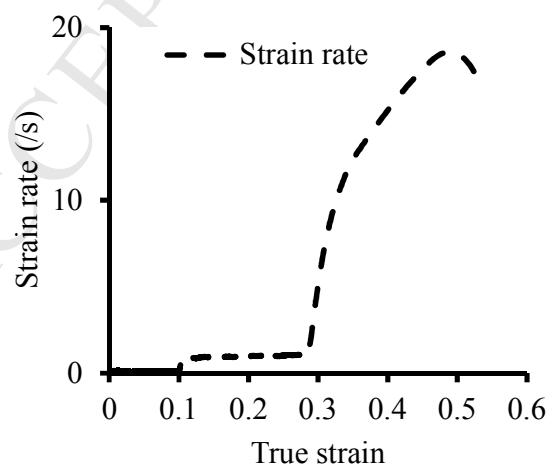


Figure 2: Strain rate vs true strain during hot deformation of alloy 3 at 500 °C

During forming processes such as extrusion and rolling, aluminum alloys are known to undergo a wide range of strain rates [12, 13]. Therefore, in order to determine the ability of the developed models in accurately predicting aluminum alloy behavior during these forming processes, hot deformation compression tests were performed on alloy 3 at 500 °C with the strain rate changing ( $\dot{\epsilon} = 0.1 \text{ s}^{-1}$  up to strain  $\epsilon = 0.099$ ,  $\dot{\epsilon} = 1 \text{ s}^{-1}$  from  $\epsilon = 0.1$  to 0.3 and  $\dot{\epsilon}$  changing from  $1 \text{ s}^{-1}$  to  $20 \text{ s}^{-1}$  for  $\epsilon = 0.3$  to 0.6) during the deformation process. Figure 2 shows the change in strain rate with respect to strain during the hot deformation compression of alloy 3 at 500 °C.

### 3. Results

#### 3.1 Flow stress curves

The stress-strain curves obtained after deformation of the Al-Mg-Si alloys at different deformation conditions are presented in Figure 3.

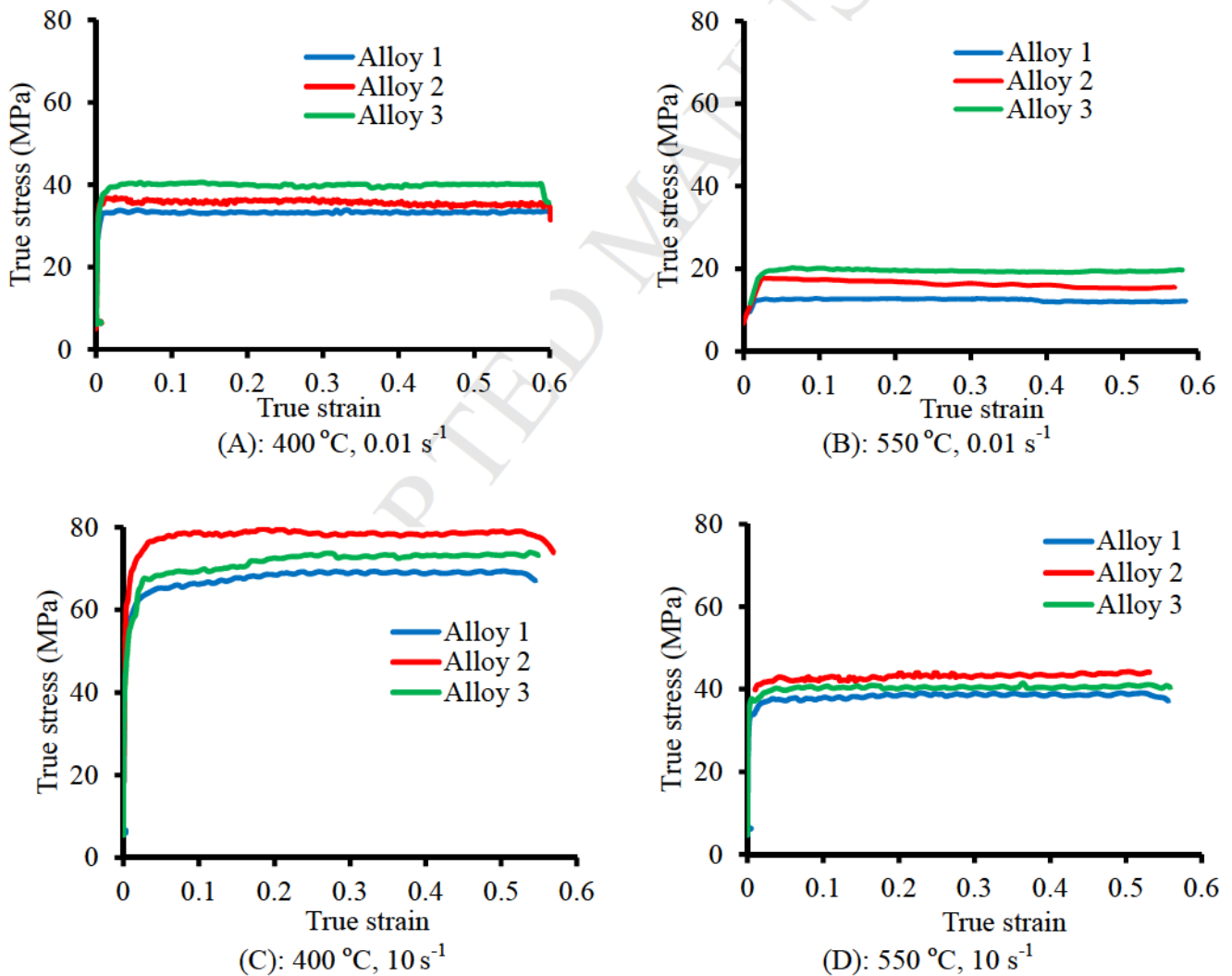


Figure 3: Typical stress-strain curve during hot compression deformation

The flow stress was observed to only change slightly with increasing strain during the deformation process. The average experimental steady state flow stress for each deformation condition was determined from the experimental flow curves as the average of stress values from a true strain of 0.1 to 0.6. In each alloy, the average flow stress was observed to increase with decreasing temperature. The average steady state flow stress for the three Al-Mg-Si alloys compressed under different deformation conditions are provided in Figure 4. The average steady state flow stress was observed to increase with increasing strain rate and decreasing temperature in each alloy. An increase in the Mg-Si content was observed to result into increase in the average flow stress for all deformation conditions as alloy 3 was observed to possess higher flow stress than alloy 1.

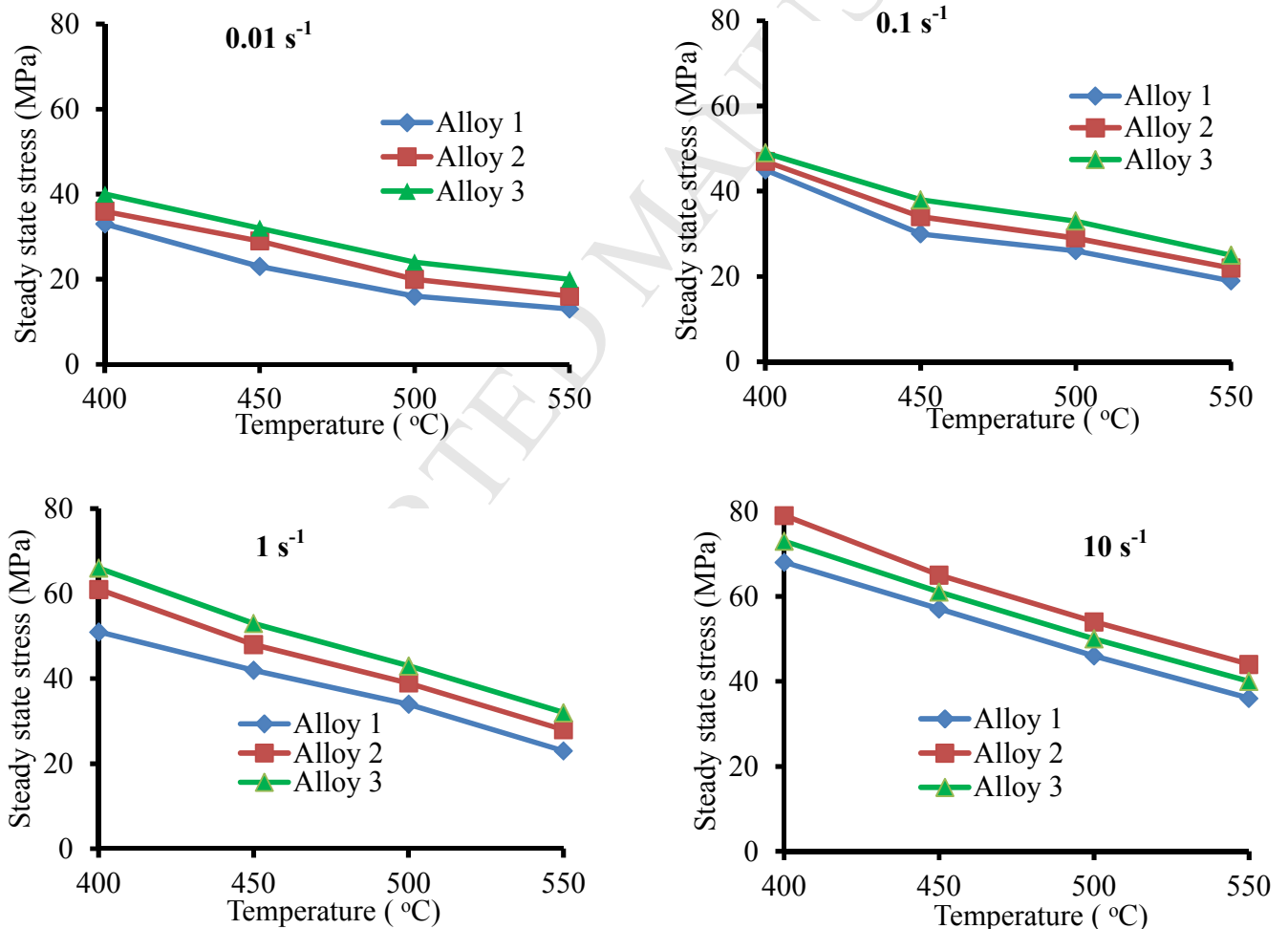


Figure 4: Average steady state stress vs temperature data

For low strain rate deformation ( $0.01-1 \text{ s}^{-1}$ ), alloy 3 with 0.2 wt % Cr was observed to possess higher average flow stress than alloy 2 with equal Mg-Si but no Cr content. However, it is worth noting that for deformation at  $10 \text{ s}^{-1}$ ; the presence of 0.2 wt % Cr did not necessarily translate into increased average flow stress as alloy 2 was observed to exhibit higher flow stress than alloy 3. During hot compression testing at low temperature ( $300-350 \text{ }^\circ\text{C}$ ), Shi and Chen [14] also observed that AA7150 aluminum alloy with 0.11-0.15 wt % vanadium content possess lower peak flow stress in comparison with alloy samples containing 0.03-0.05 wt % vanadium. However, both alloys were observed to possess equivalent flow stress at high deformation temperatures ( $400-450 \text{ }^\circ\text{C}$ ).

### 3.2 Constitutive equations

Using the well-known hyperbolic sine equation proposed by Sellars and Teggart [11], the relationship plots for alloy 1 are shown in Figure 5.

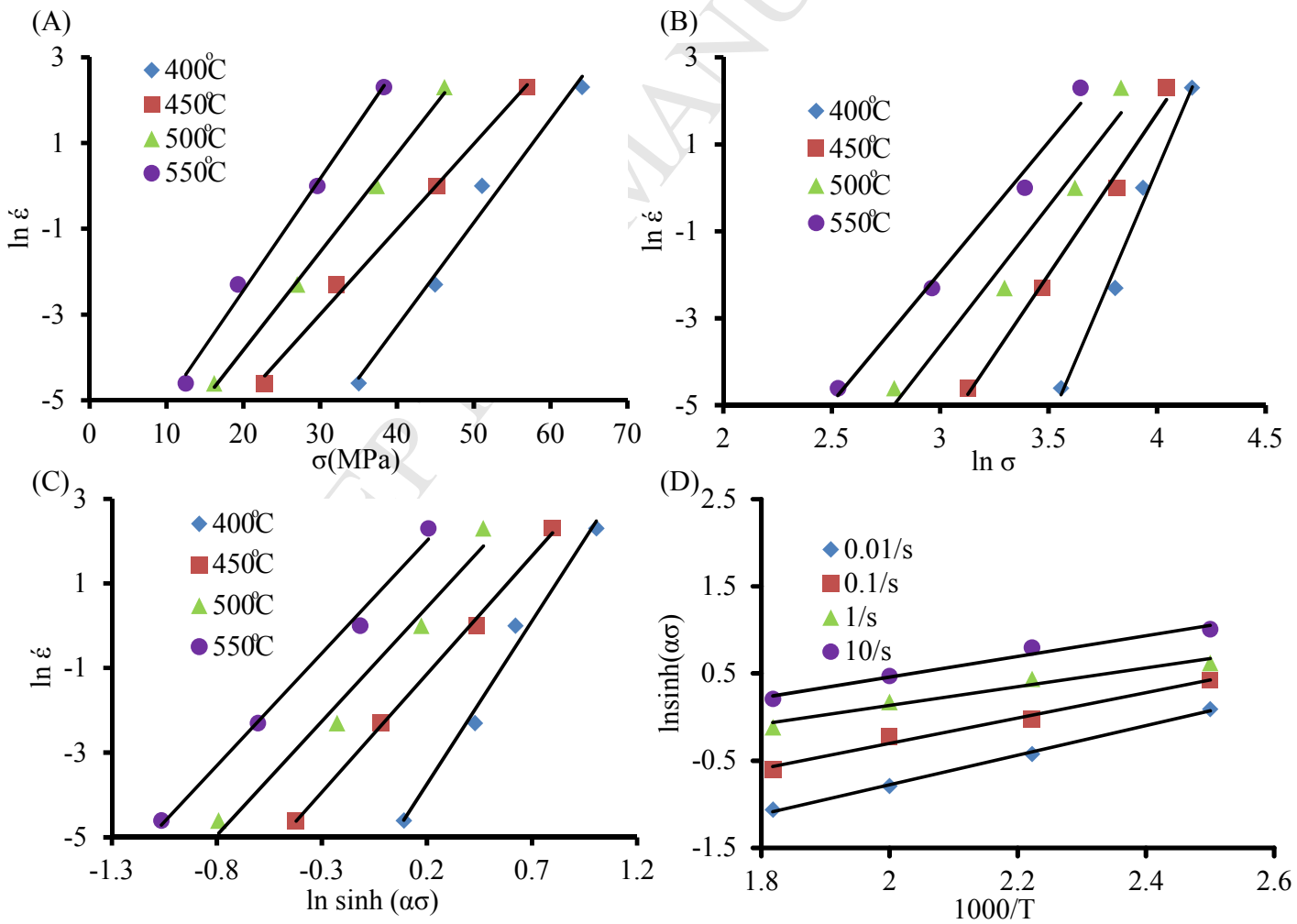


Figure 5: (A)  $\ln \dot{\epsilon}$  vs  $\sigma$ , (B)  $\ln \dot{\epsilon}$  vs  $\ln \sigma$ , (C)  $\ln \dot{\epsilon}$  vs  $\ln \sinh(\alpha\sigma)$ , (D)  $\ln \sinh(\alpha\sigma)$  vs  $\frac{1000}{T}$



The material parameters  $A$ ,  $\alpha$ ,  $n$ , activation energy for hot deformation ( $Q$ ) and strain rate sensitivity ( $m$ ) for the Al-Mg-Si alloys studied in this work were determined. The hyperbolic sine equation can be used to correlate data over a wide range of strain rates and temperature and is given as:

$$\sigma = \frac{1}{\alpha} \ln \left[ \left( \frac{Z}{A} \right)^{\frac{1}{n}} + \left( \left( \frac{Z}{A} \right)^{\frac{2}{n}} + 1 \right)^{\frac{1}{2}} \right] = \frac{1}{\alpha} \sinh^{-1} \left( \frac{Z}{A} \right)^{\frac{1}{n}}$$

where  $Z = \dot{\epsilon} \exp \left( \frac{Q}{RT} \right)$  (1)

$\sigma$  refers to the flow stress (MPa) at specific temperature  $T$  ( $^{\circ}\text{C}$ ) and strain rate  $\dot{\epsilon}$  ( $\text{s}^{-1}$ ) while  $Q$  (kJ/mol) is the deformation activation energy.  $\alpha$  is a stress multiplication factor,  $n$  refers to the stress exponent while  $R$  represents the universal gas constant ( $R = 8.314\text{J/K mol}$ ) and  $Z$  is the Zener-Hollomon parameter. The Zener-Hollomon parameter is the temperature compensated strain rate and represents the effect of temperature as well as strain rate on the deformation behavior of the alloy [15]. The parameter  $\alpha$  can be calculated as:

$$\alpha = \frac{\beta}{n_1} \quad (2)$$

Where  $\beta$  is obtained as the mean slope of the  $\ln \dot{\epsilon}$  vs  $\sigma$  graph (Figure 5(A)) and  $n_1$  represents the mean slope of  $\ln \dot{\epsilon}$  vs  $\ln \sigma$  graph shown in Figure 5(B). Only the plots for alloy 1 are presented here. The parameter  $n$  is the mean slope of  $\ln \dot{\epsilon}$  vs  $\ln [\sinh(\alpha\sigma)]$  plot shown in Figure 5(C). The activation energy for hot deformation can be determined by differentiating Eq. (1) and rearranging such that  $Q$  is given as:

$$Q = R n s = R n \frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial \left( \frac{1000}{T} \right)} \quad (3)$$

The parameter 's' in Eq. (3) is the mean slope of  $\ln [\sinh(\alpha\sigma)]$  vs  $\frac{1000}{T}$  plot obtained at constant strain rates. The parameter 'A' is determined by taking the natural logarithm of both sides of Eq. (1) to get:

$$\ln Z = \ln A + n \ln [\sinh(\alpha\sigma)] \quad (4)$$

The parameter  $\ln A$  is obtained from the intercept of the  $\ln Z$  vs  $\ln [\sinh(\alpha\sigma)]$  plot. Using the power law equation proposed by Sellars and Tegart [11], the strain rate sensitivity parameter  $m$  for each alloy was determined as the average slope of the  $\ln \sigma$  vs  $\ln \dot{\epsilon}$  plot). The material constants, activation energy and strain rate sensitivity parameter for the three alloys are shown in Table 2.

Table 2: Alloy material constants, activation energy values and strain rate sensitivity parameter

| Alloy | Q (kJ/mol) | n    | $\alpha$ (MPa) <sup>-1</sup> | A (s <sup>-1</sup> )  | m     |
|-------|------------|------|------------------------------|-----------------------|-------|
| 1     | 178        | 6.70 | 0.027                        | 7.78×10 <sup>11</sup> | 0.133 |
| 2     | 171        | 4.96 | 0.027                        | 9.72×10 <sup>10</sup> | 0.126 |
| 3     | 197        | 6.70 | 0.025                        | 6.35×10 <sup>12</sup> | 0.111 |

The constitutive equations for predicting the hot flow stress behaviour of alloys 1, 2 and 3 based on the average of stress values from a true strain of 0.1 to 0.6 are given respectively as:

$$\sigma = \frac{1}{0.027} \ln \left[ \left( \frac{Z}{7.78 \times 10^{11}} \right)^{\frac{1}{6.7}} + \left( \left( \frac{Z}{7.78 \times 10^{11}} \right)^{\frac{2}{6.70}} + 1 \right)^{\frac{1}{2}} \right] \quad (5)$$

$$\sigma = \frac{1}{0.027} \ln \left[ \left( \frac{Z}{9.72 \times 10^{10}} \right)^{\frac{1}{4.96}} + \left( \left( \frac{Z}{9.72 \times 10^{10}} \right)^{\frac{2}{4.96}} + 1 \right)^{\frac{1}{2}} \right] \quad (6)$$

$$\sigma = \frac{1}{0.025} \ln \left[ \left( \frac{Z}{6.35 \times 10^{12}} \right)^{\frac{1}{6.7}} + \left( \left( \frac{Z}{6.35 \times 10^{12}} \right)^{\frac{2}{6.70}} + 1 \right)^{\frac{1}{2}} \right] \quad (7)$$

In order to determine the accuracy of the developed model in predicting the hot flow stress behavior of the aluminum alloys over a wide range of conditions, the average experimental steady flow stress data (shown in Figure 4) were compared with predicted values obtained using equations (5)–(7) for alloys 1 to 3 respectively.

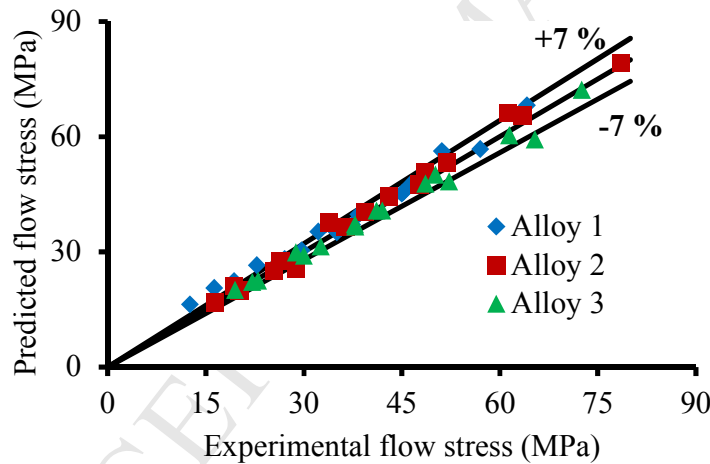


Figure 6: Comparison between predicted and experimental flow stress data at different deformation conditions

As shown in Figure 6, there exists good correlation between experimental and predicted data for the aluminum alloys tested in the current work. In order to quantitatively measure the predictive accuracy of the developed constitutive equation for determining the flow stress behavior of the aluminum alloys during hot deformation, the average absolute relative error (AARE) was calculated as [16]:

$$\text{AARE} = \frac{1}{N} \sum_{i=1}^{i=N} \left| \frac{\sigma_{exp}^i - \sigma_p^i}{\sigma_{exp}^i} \right| \times 100\% \quad (8)$$

Where  $\sigma_p$  and  $\sigma_{exp}$  are predicted and experimentally (measured) flow stress values respectively. The AARE values for alloys 1, 2 and 3 were found to be 7.2 %, 5.4 % and 3.6 % respectively.

### 3.3. Model Validation

In order to determine the effectiveness of the developed models in predicting the hot deformation behavior of Al-Mg-Si alloys at strain rates higher than the range within which the models were developed, hot deformation compression of alloy 3 was performed at  $20\text{s}^{-1}$  and  $500\text{ }^\circ\text{C}$ .

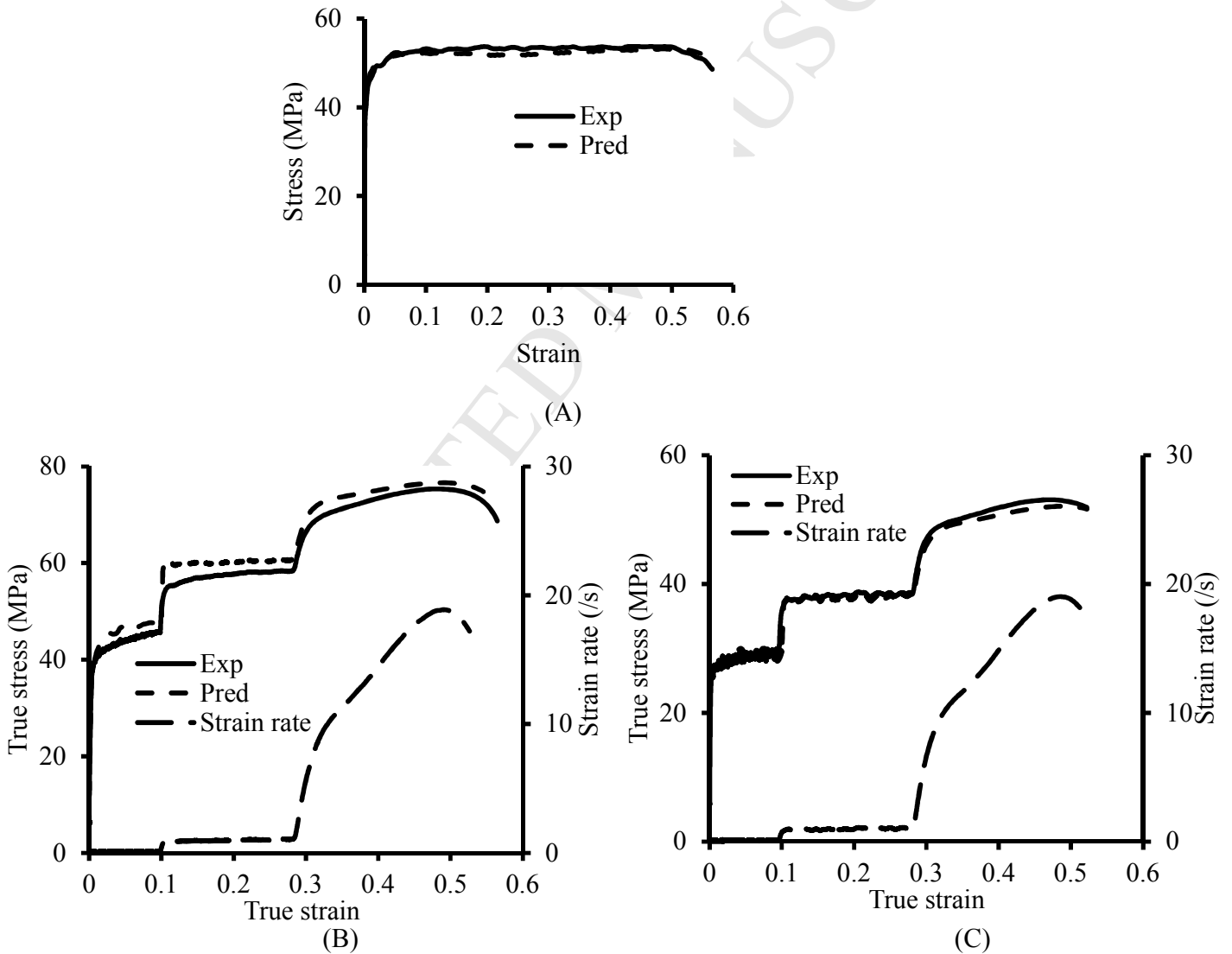


Figure 7: True stress vs strain curves for alloy 3 during deformation at varying strain rates (A):  $500\text{ }^\circ\text{C}$ ,  $20\text{ s}^{-1}$  (B):  $400\text{ }^\circ\text{C}$ , changing strain rate (C):  $500\text{ }^\circ\text{C}$ , changing strain rate

Figure 7A shows the experimental and predicted flow stress curves during the hot deformation of alloy 3 with the predicted flow stress data obtained from the developed model (Eqn. 7). As shown in Figure 7A, the developed model (Eqn. 7) was able to accurately predict the flow stress behavior of alloy 3 at  $20 \text{ s}^{-1}$  even though the model was developed within a strain rate range of  $0.01 - 10 \text{ s}^{-1}$ . Also, the predicted and experimental flow stress curves obtained during the hot compression of alloy 3 at 400 and 500 °C with strain rate changing from  $0.1 \text{ s}^{-1}$  to  $\sim 20 \text{ s}^{-1}$  during the deformation process are shown in Figures 7B and 7C. During the experiment, the temperature was held constant while the strain rate was varied with strain. The developed constitutive equation (Eqn. 7) for predicting the hot deformation behavior of alloy 3 can effectively predict the alloy's flow stress behavior during low and high temperature deformation process with strain rate changing from  $\dot{\epsilon} = 0.1 \text{ s}^{-1}$  at onset of deformation (to strain  $\epsilon = 0.099$ ) to  $\dot{\epsilon} = \sim 20 \text{ s}^{-1}$  at the end of the test. This implies that the model satisfies a necessary requirement in being able to effectively model extrusion and rolling processes where the material experiences a wide range of deformation strain rates from centre to surface during the deformation process [12].

#### 4. Discussion

Effect of alloy composition on flow stress, Q and strain rate sensitivity parameter

As seen in Table 2, alloy 3 with 0.2 wt % Cr has a higher activation energy Q value in comparison with alloy 2 possessing equal Mg and Si content but no Cr content. Also, 0.2 wt % Cr addition was discovered to result in an increase in the average steady flow stress for deformations at low strain rates ( $0.01-1 \text{ s}^{-1}$ , compare alloys 2 and 3). Aluminum alloys are known to gain strengthening via mechanisms such as cold working or work hardening, precipitation hardening, solid solution strengthening and grain refinement. The role of transition elements as grain refiners has been widely reported [17, 18]. It is believed that the higher and lower flow stress of alloy 3 in comparison to alloy 2 at low strain rates ( $0.01 - 1 \text{ s}^{-1}$ ) and high strain rate ( $10 \text{ s}^{-1}$ ) respectively is not attributable to the grain refining role of Cr as grain refinement is expected to be independent of deformation strain rate. Also, this flow stress behavior in alloy 3 cannot be attributed to precipitation hardening (deformation conditions not similar to ageing treatment) and work hardening effect (no evidence of this mechanism in the flow stress curves shown in Figure 3). Solid solution strengthening involves strengthening of Al alloys resulting from the dislocation blocking role of foreign atoms of elements in the crystal lattice of aluminum. In Cr containing

alloys, Cr solute diffusion contributes to the hot deformation kinetics process [19] and may be responsible for the increase in flow stress and activation energy. Figure 8 shows the diffusivity of Cr and other transition elements in aluminum as a function of temperature.

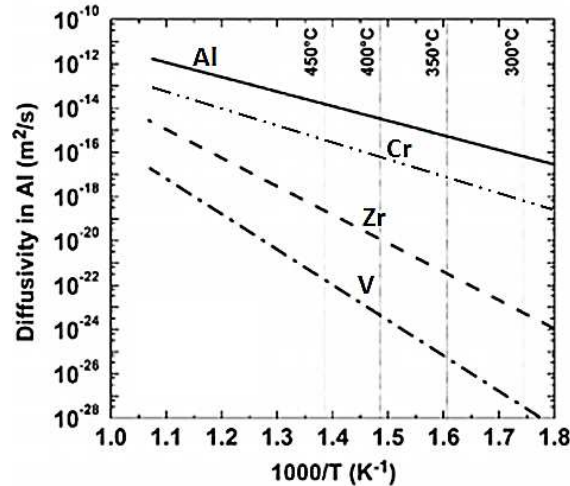


Figure 8: Diffusivity of transition elements in aluminum as a function of temperature [19]

As seen in Figure 8, for a specific temperature; Cr has a lower diffusivity in aluminum in comparison to aluminum self-diffusion. During the deformation process, solute atoms that diffuse less rapidly in aluminum in comparison with aluminum self-diffusion rate have been found to result into strengthening due to such solute atoms serving as barriers to dislocation movement [20, 21]. Cr solute atoms segregate at subgrain boundaries resulting into reduction in the energy possessed by dislocations [22]. The pinning of dislocations at subgrain boundaries implies that an increase in applied stress will be required to free dislocations. The continued blocking of dislocations by Cr solute atoms result in the multiplication of static dislocations since dislocations already blocked by Cr solute atoms now serve as barriers to the mobility of other dislocations. During hot deformation compression, the recovery process is hindered by higher solute atom vacancy binding energy which reduces vacancies available for dislocation climb and hence a decrease in dislocation mobility [23]. This result into an increase in the activation energy required for hot deformation. In their studies on creep behaviour of aluminum alloys, Rummel et al. [22] observed that the lower diffusivity of Cr in aluminum in comparison to aluminum self-diffusion is usually associated with higher activation energy in aluminum alloys with Cr content. The diffusivity of magnesium and silicon in aluminum was determined as a function of temperature by using an Arrhenius relationship given as:

$$D_i = D_i^0 \exp\left(-\frac{Q_i^d}{RT}\right) \quad (9)$$

Where  $D_i$  is the diffusivity of an element in aluminum matrix,  $R$  is the universal gas constant,  $Q_i^d$  is the activation energy for diffusion of element  $i$  in aluminum. The activation energy values for diffusion of Mg, Si and Cr in aluminum are 124 kJ/mol [24], 136 kJ/mol [24] and 64 kJ/mol [25] respectively.  $T$  represents temperature (K) and  $D_i^0$  is the diffusion parameter for element  $i$ . The diffusivity values for Mg, Si and Cr in aluminum at different temperatures are shown in Table 3.

Table 3: Mg, Si and Cr diffusivities ( $D$ ) ( $\text{m}^2/\text{sec}$ ) in aluminum as a function of temperature

| Temperature ( $^{\circ}\text{C}$ ) | $D_{\text{Mg}}$        | $D_{\text{Si}}$        | $D_{\text{Cr}}$        |
|------------------------------------|------------------------|------------------------|------------------------|
| 400                                | $1.16 \times 10^{-14}$ | $5.67 \times 10^{-15}$ | $3.11 \times 10^{-16}$ |
| 500                                | $2.05 \times 10^{-13}$ | $1.31 \times 10^{-13}$ | $1.38 \times 10^{-15}$ |
| 550                                | $6.63 \times 10^{-13}$ | $4.73 \times 10^{-13}$ | $2.69 \times 10^{-15}$ |

Cr has lower diffusivity in aluminum (Table 3) in comparison with Mg and Si at all the deformation test temperatures. Sherby and Ruano [21] reported that the deformation resistance of dilute solid solution aluminum alloys is inversely proportional to the diffusion coefficient or diffusivity of present solute atoms in aluminum. Table 4 shows that Cr has the least diffusivity in aluminum of the three elements available as solute atoms in the alloys studied and therefore the presence of its solute atoms in the Al matrix is expected to be accompanied by the highest deformation resistance. This may therefore explain the trend observed in the activation energy values for the alloys studied in this work as Mg atoms diffuse faster in Al matrix than Si and Cr solute atoms. This implies that at specific deformation temperature, Mg solute atoms in the Al matrix are less effective dislocation blocking barriers in comparison to Si and Cr solute atoms. As seen in Table 2, 0.2 wt % Cr addition has a higher influence on activation energy than Mg-Si increase. The activation energy  $Q$  was observed to increase with increase in the Mg-Si content (178 kJ/mol in alloy 1 to 197 kJ/mol in alloy 3). However, alloy 2 ( $Q = 171$  kJ/mol) with higher Mg-Si content and no Cr addition has a lower activation energy in comparison with alloy 1 where 0.2 wt % Cr is present. Alloy 3 with high Mg-Si content and 0.2 wt % Cr possesses the highest activation energy and flow stress values (during low strain rate deformation) while alloy 2 with high Mg-Si content and no Cr content possess the highest average flow stress value during high strain rate deformation. The Al-Mg-Si alloys studied in this work were observed to have higher activation energy in comparison with previously reported value of 125 kJ/mol for an Al-Mg-Si alloy with 0.49 wt % Mg, 0.4 wt % Si and no Cr content [3].

The strain rate sensitivity parameter was observed to reduce with increase in the Mg-Si content as well as with addition of 0.2 wt. % Cr. Alloy 3 with 0.6 wt % Si, 0.9 wt % Mg and 0.2 wt % Cr has the least strain rate sensitivity parameter of the three alloys studied in this work. This is consistent with available literature in which elemental additions have been observed to result in a reduced strain rate sensitivity of aluminum alloys [26, 27]. Ozturk et al. [28] also reported an increase in the strain rate sensitivity parameter for AA6061 due to reduction in the amount of free solute atoms. During deformation process, dislocations are arrested at obstacles such as clusters of mobile solute atoms [27, 29]. The pipe diffusion of these solute atoms encourages the creation of a dislocation atmosphere. However, an increase in deformation strain rate results into less dislocation arrest time which leads to dislocation freedom and therefore less stress required to accommodate applied strain. The higher diffusivities of Mg and Si in aluminum implies that the dislocation blocking role of Mg and Si solute atoms is less sensitive to reduction in arrest time associated with strain rate increase (in comparison to Cr solute atoms). This indicates that during low strain rate deformation ( $0.01-1 \text{ s}^{-1}$ ), there exists more time for Cr solute atoms to arrest dislocations and this may be responsible for the higher flow stress of alloy 3 (with Cr) in comparison with alloy 2 (no Cr). However, at higher deformation strain rate ( $10 \text{ s}^{-1}$ ); Cr dislocation arrest effect becomes minimal resulting into comparable average flow stress values for alloys 2 and 3.

## 5. Conclusions

Hot compression deformation tests of select Al-Mg-Si alloys were performed on a Gleeble 3500 thermomechanical simulator at various temperatures (400-550 °C) and strain rates ( $0.01-10 \text{ s}^{-1}$ ). The following conclusions can be made:

- (I) For all tested alloys, the average steady flow stress increases with increasing strain rate and decreasing deformation temperature. For all deformation conditions, alloy 1 (0.5Mg, 0.5Si, 0.2Cr) displayed the lowest average steady flow stress value. Alloy 3 (0.9Mg, 0.6Si, 0.2Cr) exhibited the highest flow stress at strain rates up to  $1 \text{ s}^{-1}$  while alloys 2 and 3 displayed comparable average flow stress values at  $10 \text{ s}^{-1}$ .
- (II) The hot deformation activation energy for Al-Mg-Si alloys was observed to increase (from 178 kJ/mol for alloy 1 to 197 kJ/mol for alloy 3) with increasing Mg-Si content. Also, addition of 0.2 wt % Cr was discovered to increase the activation energy for hot deformation in alloy 3 in comparison with alloy 2 with no Cr content.

- (III) An increase in the Mg-Si content and addition of 0.2 wt % Cr were observed to result into decreasing strain rate sensitivity parameter. The reduction in dislocation arrest time due to increase in deformation strain rate may be responsible for reduced Cr solute atom strengthening in alloy 3.

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**HIGHLIGHTS**

1. Effect of alloy composition on hot deformation flow stress behavior of Al-Mg-Si alloys was investigated
2. Activation energy for hot deformation of Al-Mg-Si alloys increase with an increase in Mg-Si content and addition of 0.2 wt % Cr
3. Developed constitutive models can accurately predict Al-Mg-Si alloy deformation behavior over wide range of temperature and strain rate – a requirement for accurately predicting alloy deformation behavior during forming processes such as extrusion
4. The strain rate sensitivity parameter of Al-Mg-Si alloys was observed to reduce with an increase in Mg-Si content and addition of 0.2 wt % Cr