Phenomenological-based constitutive modelling of warm deformation behavior of high-Strength lightweight AL-Li alloy sheets

A Abd El-Aty1*, Y Xu2, S H Zhang2, X Guo3, J Tao3, M G Lee1*

1Department of Materials Science and Engineering & Research Institute of Advanced Materials (RIAM), Seoul National University, Seoul 08826, Republic of Korea.
2Institute of Metal Research, Chinese Academy of Sciences, Shenyang, 110016, P.R. China
3College of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 211100, P. R. China.

E-mail: aabdelaty@nuaa.edu.cn
myounglee@snu.ac.kr

Abstract. The flow behavior and formability of Al-Li alloys under warm forming conditions are complicated because they depend on several factors, such as the deformation mode, strain, and strain rates. Therefore, characterizing the mechanical response, and deformation behavior of AA2060-T8 sheets under a wide range of temperatures and strain rates is crucial to develop a new thermo-mechanical processing (TMP) route for their wide industrial applications. Furthermore, determining the activation energy (Q) and predicting the flow behaviour of AA2060-T8 sheets under warm forming temperatures is meaningful for characterizing the mechanical response of AA2060-T8 sheets at warm deformation conditions. Thus, in this study, the Arrhenius constitutive model is developed to investigate the influence of strain rate and temperature on the warm deformation behaviour of AA2060-T8 and determine the activation energy (Q) of AA2060-T8, which is a crucial physical parameter to estimate the difficulties of deforming AA2060-T8 sheets under warm forming conditions.

1. Introduction
Presently, the third generation of Al-Li alloys has demonstrated promise as materials for the components used in military, aircraft, and aerospace applications due to their outstanding physical and mechanical properties [1]. One of the newest candidates in the family of the third generation Al-Li alloys is AA2060-T8 alloy which launched by Alcoa Inc. in 2011 to take the place of AA7075-T6 and AA2024-T3 for fuselage structures and lower, and upper wings [2]. Although AA2060-T8 possesses superior physical and mechanical properties, its board applications are restricted notably at room temperature because of poor formability; anisotropic behavior which caused serious issues during deformation; and
springback and wrinkling which are in turn add to the cost of the die and the final components due to the try-out time [3, 4]. Forming at elevated temperatures [5] are considered as significant methods to address the above-mentioned shortcomings of AA2060-T8 sheets and minimize the drawbacks of forming this alloy using traditional cold forming technologies. Hence, it is vitally important to reveal the deformation behavior and the constitutive relations which describe the material flow of AA2060-T8 sheets under warm forming conditions for manufacturing sound thin-walled complex shaped components from AA2060-T8 sheets.

Warm forming technologies are considered as significant techniques to address the drawbacks of cold forming and improve the formability AA2060-T8 sheets [6]. During warm forming, the sheets are subjected to different types of strain under a wide range of temperatures and strain rates. Once the strain reached a threshold value, various types of failures (e.g., necking, wrinkling, fracture, and buckling) may occur. This phenomenon is very interesting and important in sheet metal forming. The flow behavior and formability of Al-Li and Al alloys under warm forming conditions are complicated because they depend on several factors, such as the deformation mode, strain, and strain rates [7-10]. These factors control the strain hardening, which in turn affects the flow behavior and formability of Al-Li and Al alloys [10, 11]. Therefore, characterizing the mechanical response, fracture mechanisms, and deformation behavior of AA2060-T8 sheets under a wide range of temperatures and strain rates is crucial to develop a new thermo-mechanical processing (TMP) route for their wide industrial applications. Furthermore, determining the activation energy (Q), and predicting the flow behavior of AA2060-T8 sheets under warm forming temperatures is meaningful for characterizing the mechanical response of AA2060-T8 sheets at warm deformation conditions. Within this realm, constitutive modelling is usually used to predict the flow behavior of materials in a form that can be used in finite element (FE) codes to simulate the mechanical response of materials under different forming conditions [11].

The motivation of this study is to understand the deformation behavior of AA2060-T8 sheets under warm forming conditions. Thus, this paper starts with investigating the adiabatic heating influence on the stress-strain behaviors of AA2060-T8 sheets. Then, the details of Arrhenius constitutive model to determine the activation energy (Q) of AA2060-T8 is introduced. Q is a crucial physical parameter to estimate the difficulties of plastically deforming the metallic materials.

2. Materials Description and Experimental Procedures

The material used in this investigation is AA2060-T8 alloy, which is a new member of the third-generation Al-Li alloy. AA2060-T8 was produced in 2011 by Alcoa Company for use instead of Al Alloys such as AA7075 and AA2024 in aerospace structures [1]. The microstructure and chemical composition of the as-received sheet of 2060-T8 Al-Li alloy are presented in Fig. 1 and Table.

In this investigation, a Gleeble-3800 material simulator was used to perform the isothermal warm tensile testing at 100°C, 150°C, 200°C, 250°C, and 300°C and strain rate of 0.001 to 10 s−1 strain rates. The details of the test are introduced in Fig. 2. Each experiment was performed three times at least to make sure from repeatability and consistency. The mean values of the three repetitions are considered. Besides, all the experiments contain equal amounts of data and thus are weighted equally. The deformation temperatures were characterized by the welded thermocouples fixed in the middle of the gauge lengths of the tensile specimens and provided signals for accurate feedback, as depicted in Fig. 2. The strain rates, working temperatures, and strains were automatically controlled and reported. Before the warm tensile testing, the specimens heated until the required working temperature.
Fig. 1. The microstructure of the as-received AA2060-T8 sheet

Table 1. Uniaxial tensile experiments matrix under warm forming conditions.

| Strain rate (s\(^{-1}\)) | 100 | 150 | 200 | 250 | 300 |
|--------------------------|-----|-----|-----|-----|-----|
| 0.001, 0.01, and 0.1 s\(^{-1}\) | ✓   | ✓   | ✓   | ✓   | ✓   |

Fig. 2. The details of tensile area Gleeble-3800 materials simulator.

3. Results and Discussions

3.1. Stress-strain behavior

The experimental true stress-strain (\(\sigma_t - \varepsilon\)) curves of AA2060-T8 sheets obtained from the isothermal warm tensile tests using Gleeble material simulators under warm forming conditions and using the samples machined in rolling direction are depicted in Figs. 3 and 4. These (\(\sigma_t - \varepsilon\)) curves possess common scale to visualize the direct influences of strain rates and temperature on the deformation behavior of this alloy effectively. As shown in these (\(\sigma_t - \varepsilon\)) curves, the overall shapes of the flow curves were dependent on temperature and strain rates. Thus, the influences of temperature and strain rate on the deformation behavior and fracture mechanisms are discussed in the next sections. Furthermore, the shapes of these (\(\sigma_t - \varepsilon\)) curves pointed out some vital characteristics which are helpful to identify the deformation mechanism of AA2060-T8 sheets.
When AA2060-T8 tensile sample was subjected to tensile loading, the mobile dislocations were interacted with the dislocation networks exist in this alloy. Since the structures of the dislocation strongly hinder the dislocations movements, the strength of this alloy tends to increase with increasing strain rate and decreasing the forming temperature. As shown in Figs. 3 and 4, the \((\sigma_t - \varepsilon)\) curves of AA2060-T8 sheets are composed of four stages: stage I (elastic stage); stage II (work hardening stage); stage III (softening stage); and finally, stage IV (steady stage). In the elastic stage, the stresses are linearly proportional to the strains, and by increasing the stresses, the strain exceed the elastic region. At the beginning of deformation (i.e., strain hardening stage), the rapid increase in stresses is associated with increasing in dislocation density, thus, the strain hardening exceeds the dynamic softening. As the plastic deformation progresses (softening stage), the activation of the dynamic softening can partially or completely or offset the influence of strain hardening. At the point of ultimate tensile stress, the strain hardening as well as dynamic softening become balance, therefore, the flow stress decreases slowly or remains unchanged. In general, Strain hardening was attributed to many pinned dislocations of little mobility which led to increase the density and mutual intersection of dislocation under the external stresses. On the other hand, the dynamic softening may result in the microstructures with lower energies induced by reorganization of dislocations and the decreasing the dislocations densities [11].

3.2. Corrections of the adiabatic heating influence.

All the \((\sigma_t - \varepsilon)\) curves of AA2060-T8 sheets in Figs.3, and 4 are depended on the initial temperatures of the tensile specimens. Nevertheless, the actual temperature of the tensile specimen is different from the initial one. This is attributed to the conversion of the plastic work into heat and the losses by radiation, convection, and conduction from the specimen to its surroundings. At low strain rates (i.e., \(\dot{\varepsilon} \leq 1\) s\(^{-1}\)), the deformation process is assumed to be isothermal since the rise in temperature during deformation process is ignored. In contrast, at high strain rates (i.e., \(\dot{\varepsilon} \geq 1\) s\(^{-1}\)), the deformation process is adiabatic, thus, the rise in temperature cannot be neglected during deformation and the temperature needs to be corrected to consider the adiabatic effect. Ou et al. [10] mentioned in their investigation that adiabatic heating correction should be applied if the strain rate exceeding 1 s\(^{-1}\). Thus, in this study, the incremental procedure proposed by [12] was used for calculating the temperature increase during tensile testing. They assumed that the rise in temperature is homogeneous throughout the tensile specimen and the variation in specific heat \((C)\) and density \((\rho)\) during the temperature interval \((\delta T)\) is neglectable. Thus, the rise in temperature was calculated using Eq. 1.

\[
\int_{T_0}^{T_0+\delta T} \rho C dT = \int_{\varepsilon_0}^{\varepsilon_0+\delta \varepsilon} \sigma d\varepsilon \Rightarrow \delta T = \frac{\delta \varepsilon}{\rho C} \tag{1}
\]

where \(\bar{\sigma}\) is the mean stress which calculated from the \((\sigma_t - \varepsilon)\) curve of each forming temperature (i.e., 100°C, 150°C, 200°C, 250°C, 300°C) and strain rate of 10 s\(^{-1}\) over the strain interval \(\delta \varepsilon\) by using trapezoid equation:

\[
\bar{\sigma} = \frac{1}{\delta \varepsilon} \int_{\varepsilon_0}^{\varepsilon_0+\delta \varepsilon} \sigma d\varepsilon \tag{2}
\]

Thus, the influence of the rise in temperature on the flow stress was assessed using the following equation:

\[
\delta \sigma = \left[ \frac{\delta \sigma}{\delta (1/T)} \right]_{\sigma_t=\varepsilon} \left[ \frac{1}{T_{iso}+\delta T} - \frac{1}{T_{iso}} \right] \tag{3}
\]

Fig. 4 shows the corrections of the adiabatic heating influence on \((\sigma_t - \varepsilon)\) curve of AA2060-T8 sheets at different forming temperatures, and strain rate of 10 s\(^{-1}\). At higher strain rates, and lower forming temperatures, the raise in normalized temperature is increased because of the higher flow stresses. Hence, as shown in Fig. 4, the difference between uncorrected and corrected and curves is reduced with increasing the forming temperature because of the decrease of the alloy strength.
4. Phenomenological-based Constitutive modelling

It is indispensible to propose constitutive equations to reveal and predict the deformation behavior of AA2060-T8 sheets under warm forming conditions. Within this realm, Arrhenius constitutive model is effective phenomenological-based constitutive models to describe the correlation between flow behavior, strain rate and temperature. Thus, in this study, Arrhenius constitutive model is used as the constitutive model of AA2060-T8 sheets to determine the activation energy \( Q \) of AA2060-T8. \( Q \) is crucial physical parameter to estimate the difficulties of plastically deforming the metallic materials.

The combined influence of strain rate and temperature on warm/hot deformation behavior of metals can be characterized by Zener–Hollomon parameter \( Z \) which is defined by exponent type equation [12-13] as:

Fig. 3. True stress-strain curves of AA2060-T8 sheets at RD, different forming temperatures (i.e. 100°C, 150°C, 200°C, 250°C, 300°C), and strain rates of (a) 0.001 s\(^{-1}\), (b) 0.01 s\(^{-1}\), and (c) 0.1 s\(^{-1}\).

Fig. 4. Correction of adiabatic heating influence on the true stress-strain curves of AA2060-T8 at forming temperatures of 100°C, 150°C, 200°C, 250°C, and 300°C, and strain rate of 10 s\(^{-1}\).
\[ Z = \dot{\varepsilon} \exp \left( \frac{Q}{RT} \right) \]  
(4)

where, \( \dot{\varepsilon} \) is the strain rate, \( Q \) is the activation energy of warm/hot deformation, \( T \) is the absolute temperature, and \( R \) (8.31 J mol\(^{-1}\) K\(^{-1}\)) is the universal gas constant.

The relationship between deformation temperature, strain rate, and flow stress, notably at elevated temperature, can be represented by the Arrhenius constitutive model [13] as:

\[ \dot{\varepsilon} = A F(\sigma) \exp \left( -\frac{Q}{RT} \right) \]  
(5)

where \( F(\sigma) \) can be expressed as power law equation (Eq. 6), or as exponent type equation (Eq. 7) or hyperbolic sine type equation (Eq. 8) as follow:

\[ F(\sigma) = \sigma^{n_1} , \quad \text{if } \alpha \sigma < 0.8 \]  
(6)

or

\[ F(\sigma) = \exp (\beta \sigma) , \quad \text{if } \alpha \sigma > 1.2 \]  
(7)

or

\[ F(\sigma) = [\sinh (\alpha \sigma)]^{n_1} , \quad \text{for all } \sigma \]  
(8)

\( A, n, n_1, \) and \( \beta, \alpha \) are material constants, as well as \( \sigma \) is the flow stress. For Al alloys, \( \sigma \) can be practically replaced in the constitutive equations by maximum flow stress (\( \sigma_p \)). This assumption is compatible with previous investigations on titanium alloys, magnesium alloys, and steel [10-12]. \( \alpha \) is the stress multiplier which is essential to establish the constitutive model of AA2060-T8 under warm forming conditions. For Al alloys, \( \alpha \) is varying from 0.01 to 0.08 MPa\(^{-1}\) [12]. \( \alpha \) is usually calculated by:

\[ \alpha = (\beta/n_1) \]  
(9)

\( \beta, \) and \( n_1 \) are calculated from the slopes of the relations between (\( \log \dot{\varepsilon} - \sigma_p \)), and (\( \log \dot{\varepsilon} - \log \sigma_p \)), respectively. Thereafter, by substituting the values of = 0.113568 , and \( n_1 = 6.24 \) in Eq. (9), \( \alpha \) was calculated as 0.01392 MPa\(^{-1}\).

In this study Eq. (8) is used to describe the relationship between flow stress, true strain, forming temperature, and strain rates, since it can be used for all stress level. In contrast, Eqs. (6), and (7) are preferred in case of low stress (\( \alpha \sigma < 0.8 \)) such as creep, and high stress (\( \alpha \sigma > 1.2 \)), respectively [12]. Thus, the constitutive equation of AA2060-T8 sheets under warm forming conditions can be expressed as:

\[ \dot{\varepsilon} = A [\sinh (\alpha \sigma)]^{n_1} \exp \left( -\frac{Q}{RT} \right) \]  
(10)

To quantitatively investigate the warm deformation behavior of AA2060-T8 sheets, \( A, \alpha, n, \) and \( Q \) are calculated by differentiating Eq. (10) as follows:

\[ Q = R n \left| \frac{\partial \ln [\sinh (\alpha \sigma)]}{\partial (1/T)} \right|_{\dot{\varepsilon}} \]  
(11)

\[ n = \left| \frac{\partial \ln \dot{\varepsilon}}{\partial \ln [\sinh (\alpha \sigma)]} \right|_T \]  
(12)

By combining Eqs. (11) and (12), \( Q \) can be calculated by:

\[ Q = R \left| \frac{\partial \ln \dot{\varepsilon}}{\partial \ln [\sinh (\alpha \sigma)]} \right|_T \left| \frac{\partial \ln [\sinh (\alpha \sigma)]}{\partial (1/T)} \right|_{\dot{\varepsilon}} \]  
(13)

\( A, n, \) and \( Q \) are calculated from the linear fitting of the of the relations (\( \ln [\sinh (\alpha \sigma)] \)) – (\( 1/T \)) and (\( \ln [\sinh (\alpha \sigma)] \)) – (\( \ln \dot{\varepsilon} \)). Hence, \( A = 4.13 \times 10^{10} \text{s}^{-1}, n = 6.24, \) and \( Q = 242 \text{ kJ mol}^{-1} \) are listed in Table 2. Thus, the final constitutive equation of AA2060-T8 sheets can be expressed as:

\[ \dot{\varepsilon} = 4.13 \times 10^{10} [\sinh (0.01392 \sigma)]^{6.24} \exp \left( -\frac{242}{RT} \right) \]  
(14)
Table 2. The material constants and activation energy ($Q$) of AA2060-T8

| A (s$^{-1}$) | $\alpha$ (MPa$^{-1}$) | n | Q (kJ mol$^{-1}$) |
|-------------|----------------------|---|------------------|
| $4.13 \times 10^{10}$ | 0.01392 | 6.24 | 242 |

5. CONCLUSIONS

The main conclusions can be deduced as follows:

(1) Below forming temperature of 250°C, strain hardening is dominated over the dynamic softening mechanisms. However, at 250°C and above, the DRV is dominated, and the strain hardening is gradually disappeared. Thus, DRV is the primary reason of causing softening effect and reducing the effect of strain hardening in AA2060-T8 sheets at the temperature of 250°C and above.

(2) The flow stress can be represented by a Zener-Hollomon parameter in the hyperbolic-sine equation with the warm deformation activation energy of 242 kJ/mol, and the final constitutive equation of AA2060-T8 sheets can be expressed as: $\dot{\varepsilon} = 4.13 \times 10^{10}[\sinh(0.01392\sigma)]^{6.24} \exp\left(-\frac{242}{RT}\right)$.

References

1. Abd El-Aty A, Xu Y, Guo X, Zhang S, Ma Y, Chen D 2018. J Adv Res. 10: 49-67.
2. Abd El-Aty A, Xu Y, Zhang S, Ma Y, Chen D 2017. Procedia Eng. 207:13-18.
3. Abd El-Aty A, Xu Y, Zhang S, Ha S, Yan Y, Chen D 2019. J Adv. Res. 18:19-37.
4. Abd El-Aty A, Xu Y, Ha S, Zhang S H 2018. Mater Sci Eng A. 731:583-594
5. Abd El-Aty A, Zhang S, Xu Y, Ha S 2019. J Mater Res Technol. 8:1235-1249.
6. Abd El-Aty A, Zhang S, Guo X, Xu Y, Yan M, Chen D, Tao J. 2021. The Minerals, Metals & Materials Series. Springer, Cham
7. Xu Y, Abd El-Aty A, Zhang S, Ma Y, Chen D 2019. IOP Conf. Ser.: Mater. Sci. Eng. 651 (2019).
8. Lin Y, Chen X. 2011. Mater Des. 32:1733-1759.
9. Zheng K, Politis D, Wang L, Lin J 2018. Int. J. Light. Mater. Manuf. 1:55-80
10. Ou L, Zheng Z, Nie Y, Jian H 2015. J Alloys Compd. 648:681-689.
11. Gao H, Weng T, Liu J, Li C, Li Z, Wang L 2016. Manufacturing Rev. 9:9-15.
12. Liang H, Nan Y, Ning Y, Li H, Zhang L, Shi Z, Guo H 2013. J. Alloy. Compd. 632(25):478-485.

Acknowledgements

The authors greatly acknowledge the financial support from National Natural Science Foundation of China - International (Regional) Cooperation and Exchange Program (No. 5201101342), and Jiangsu Province Science and Technology Project (No. BK20200453), and the National Natural Science Foundation of China (Grand No. 51875548).