

INVESTIGATION ON HOT DEFORMATION BEHAVIOR OF AL-CU-MG-PB ALLOY

H.R. Rezaei Ashtiani*, P. Shahsavari

Department of Mechanical Engineering, Arak University of Technology, Arak, Iran.

* Email of corresponding author: hr_Rezaei@arakut.ac.ir

ABSTRACT: In order to find material parameters of established Zener-Hollomon constitutive equations and predict high-temperature flow stress of Al-Cu-Mg-Pb alloy, isothermal hot compression tests were conducted at constant strain rates of 0.005, 0.05 and 0.5 s⁻¹ and at temperatures ranging from 623 to 773 K at intervals of 50K. The results show that the flow stress of Al-Cu-Mg-Pb alloy increases with increasing strain rate and deformation temperature decreasing, which is characterized by work-hardening, dynamic recovery, dynamic recrystallization. The effects of strain rate and temperature on hot deformation behavior were represented by Zener-Hollomon parameter including Arrhenius term. The power law, exponential, and sin hyperbolic types of Zener-Hollomon equations were used to determine the hot deformation behavior of Al-Cu-Mg-Pb alloy. The results suggested that the highest correlation coefficient was achieved for the hyperbolic sine law for the studied material. So the proposed deformation constitutive equations can be used for numerical simulation of hot forming processes and for choosing proper forming parameters in engineering practice accurately.

KEYWORDS: hot deformation, constitutive equation, flow stress, hyperbolic sine law, Al-Cu-Mg-Pb alloy.

1.0 INTRODUCTION

Lightweight materials have played a significant role in the advance and development of many aviation applications. Speed, long range, as well as operational cost are the obvious factors in determining the aircraft performance [1]. Aluminum and its alloys are still the

dominant materials for aircraft structure. In particular, Aluminum alloys of the 2000 series such as Al-Cu-Mg and Al-Cu-Mg-Pb alloys are very used in aeronautical applications due to the high strength to weight ratio associated with good fracture toughness, good corrosion resistance and excellent high temperature characteristics. Generally, these series of aluminum alloys will be subject to various hot forming processes, such as rolling, forging, extrusion, and heat treatments [2, 3].

The understanding of metals and alloys behavior at hot deformation condition has a great importance for designers of metal forming processes (hot rolling, forging and extrusion) because of its effective role on metal flow pattern as well as the kinetics of metallurgical transformation. Based on metallurgical factors, some various constitutive equations of materials were developed from the experimentally measured data to describe the sensitivity of the flow stress to the strain, strain rate and temperatures in commercial hot working applications [4-6]. In general, constitutive equations which represent the hot deformation behavior of different materials are cited as essential input to the FEM code for simulating the materials forming processes under different deformation conditions [7, 8]. Nevertheless, numerical simulation results can be truly credible only when the precision of the constitutive equation is high enough.

Many researchers have tried to predict the mechanical behavior of materials in the hot working condition using constitutive models. Therefore, various constitutive equations have been proposed to describe the flow behavior, which including phenomenological, physically based and artificial neural network (ANN) models [9, 10]. A phenomenological approach was proposed by Jonas et al. where the flow stress is expressed by the hyperbolic laws in an Arrhenius type of equation [11]. The Arrhenius equation is widely used to describe the relationship between the strain rate, deformation temperature, and flow stress, especially at elevated temperature. It can also be shown with Zener-Hollomon parameter [12]. Scientists and researchers have made efforts to develop constitutive equations

of materials from the experimentally measured data to describe the hot deformation behaviors of metals and alloys by the hyperbolic laws in an Arrhenius type of equation. In most studies, the hyperbolic sinusoidal law in Arrhenius type equation gives better approximation between Zener–Hollomon parameter and stress [13-16], although in some cases power law is the most appropriate constitutive equation [17].

In this paper, hot compression test was used to perform forging simulation of Al-Cu-Mg-Pb alloy to investigate the variation rule of flow stress during compressive deformation. The main objective of this study is to derive a proper constitutive equations relating flow stress, strain rate and forming temperature of Al-Cu-Mg-Pb alloy at high temperatures.

2.0 EXPERIMENTAL PROCEDURE

The material used in this investigation is the Al-Cu-Mg-Pb alloy, and its chemical composition has been given in Table 1.

Table 1: Chemical composition (wt. %) of Al-Cu-Mg-Pb alloy.

Cu	Mg	Pb	Si	Fe	Mn	Zn
3.85	0.92	1.12	0.37	0.58	0.25	0.37

Cylindrical specimens were machined with a diameter of 8 mm and a height of 12 mm. In order to minimize the frictions between the specimens and die during hot deformation was use a very thin mica sheet, since the interfacial friction has some negative effects on the accuracy of the calculated true stress-strain data. The hot compression tests were performed in the temperature range of 623-773 K and strain rate range of 0.005-0.5 s⁻¹. The specimens were firstly heated to the deformation temperature and then held for 5 min to ensure a homogenous temperature distribution throughout the specimen. When the reduction of the specimens reached 60%, the hot

compression tests were finished and the deformed specimens were quenched into cool water immediately.

3.0 RESULTS AND DISCUSSION

3.1 FLOW STRESS BEHAVIOR

The typical true stress-strain curves of Al-Cu-Mg-Pb alloy under different deformation conditions are shown in Figure 1. It is noted that the flow stresses are strongly dependent on the deformation temperature and strain rate under all the tested conditions. The deformation resistance increases with the decrease of deformation temperatures for a given strain rate and decreases with the decrease of strain rates for a given deformation temperature. The material simultaneously experiences both work hardening and dynamic recovery when they are deformed. The work hardening and dynamic recovery will in turn affect the mechanical properties of material during hot deformation.

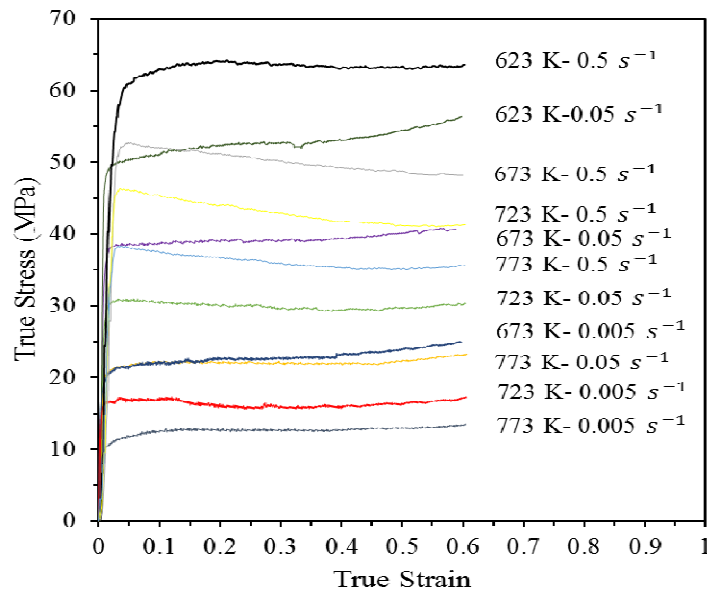


Figure 1: True stress–true strain curves for various deformation temperatures and strain rates.

3.2 CONSTITUTIVE EQUATION OF FLOW STRESS

Constitutive equations are usually used to estimate the flow stresses of a material during deformation and the strain–stress data obtained from compression tests under different strain rate and temperature conditions can be used to determine the material constant of these equations. Some research reports have shown that Arrhenius model has high accuracy in describing the flow stress, especially at high deformation temperature. It is well accepted that the correlation between flow stress, temperature and strain rate could be described by the power law of Equation (1) in low stress level, and by the exponential law of Equation (2) in high stress level.

$$\dot{\epsilon} = A_1 \sigma^{n'} \exp\left(-\frac{Q}{RT}\right) \quad (\alpha\sigma < 0.8) \quad (1)$$

$$\dot{\epsilon} = A_2 \exp(\beta\sigma) \exp\left(-\frac{Q}{RT}\right) \quad (\alpha\sigma > 1.2) \quad (2)$$

Where, σ is the flow stress (MPa) for a given strain, T is the absolute temperature (K), R is the universal gas constant (8.3144 J mol⁻¹K⁻¹), Q is the deformation activation energy (J mol⁻¹); and A_1, A_2, n' and β are material constants. For the entire range of stress, a hyperbolic sine-type equation is more suitable, which is expressed as,

$$\dot{\epsilon} = A[\sinh(\alpha\sigma)]^n \exp\left(-\frac{Q}{RT}\right) \quad (3)$$

Where A and n are the material constants, α is the stress multiplier and also the additional adjustable parameter, which is calculated as $\alpha = \beta/n'$.

Combined strain rate and temperature dependence of the flow stress during deformation could be expressed by Zener–Holloman parameter (Z) in an exponent-type equation [18], as shown on Equation (4).

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right) \quad (4)$$

The Zener-Hollomon parameter, the physical meaning of which is the so-called temperature compensated strain rate parameter. Generally, Z can be used to characterize the combined effect of strain rate and temperature on the deformation process, especially the deformation resistance.

3.3 DETERMINATION OF MATERIAL CONSTANTS

Flow stress versus true strain data obtained from the HOT compression tests at various processing conditions, such as deformation temperature and strain rate, were employed to evaluate the materials constants of the constitutive equations. The following are the evaluation procedure of material constants at peak stress. For the low and high stress levels will be substituted the power law (Equations (5)) and exponential law (Equations (6)) respectively, whereas Equation (6) is used for all level of stress.

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right) = A_1 \sigma_p^{n'} \quad (5)$$

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right) = \exp(\beta \sigma_p) \quad (6)$$

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right) = A [\sinh(\alpha \sigma)]^n \quad (7)$$

Taking the logarithm of both sides of Equations (5) and (6), respectively, Equations (8) and (9) can be obtained.

$$\ln \sigma_p = \frac{1}{n'} \ln \dot{\epsilon} + \frac{Q}{n' RT} - \frac{1}{n'} \ln A_1 \quad (8)$$

$$\sigma_p = \frac{1}{\beta} \ln \dot{\epsilon} + \frac{Q}{\beta RT} - \frac{1}{\beta} \ln A_2 \quad (9)$$

Then, replacing of the flow stresses values and corresponding strain

rates values under the peak stress into the logarithm Equations (8) and (9) gives the relationship between the peak flow stress and strain rate as shown in Figure 3. It can be observed that the flow stresses are well fitted by a group of straight lines. With considering that the hot deformation process is carried out at constant temperature, the partial differentiation of Equations (8) and (9) yields Equations (10) and (11), respectively.

$$n' = \left[\frac{\partial \ln \dot{\epsilon}}{\partial \ln \sigma_p} \right]_T \quad (10)$$

$$\beta = \left[\frac{\partial \ln \dot{\epsilon}}{\partial \sigma_p} \right]_T \quad (11)$$

Where values of n' and β are acquired through linear regression of data, and average slopes from the slope of every single line in the $\ln \sigma_p - \ln \dot{\epsilon}$ and $\sigma_p - \ln \dot{\epsilon}$ are shown in Figure 3. The average values of n' and β can be calculated as 5.0669 and 0.1592 MPa^{-1} and then $\alpha = \beta/n' = 0.032 \text{ MPa}^{-1}$.

Taking the natural logarithm of both sides Equation (7) for all range of stress level, gives:

$$\ln[\sinh(\alpha \sigma_p)] = \frac{\ln \dot{\epsilon}}{n} + \frac{Q}{nRT} - \frac{\ln A}{n} \quad (12)$$

Differentiating Equation (12) gives:

$$Q = R \left[\frac{\partial \ln \dot{\epsilon}}{\partial \ln[\sinh(\alpha \sigma_p)]} \right]_T \left[\frac{\partial \ln[\sinh(\alpha \sigma_p)]}{\partial (1/T)} \right]_{\dot{\epsilon}} \quad (13)$$

Therefore, by substituting the values of forming temperatures, strain rates and corresponding stresses into Equation (13), the value of Q can be derived from the slopes of the lines in the $\ln[\sinh(\alpha \sigma_p)] - \ln \dot{\epsilon}$ plot for a constant temperature and so for a constant strain rates can be derived from the slope of plotting $\ln[\sinh(\alpha \sigma_p)] - 1/T$ at fixed strain,

as shown in Figures 4(a) and 4(b), respectively. The value of Q can be determined by averaging the values of Q under different strain rates and forming temperature which was computed to be 98.213 KJ/mol.

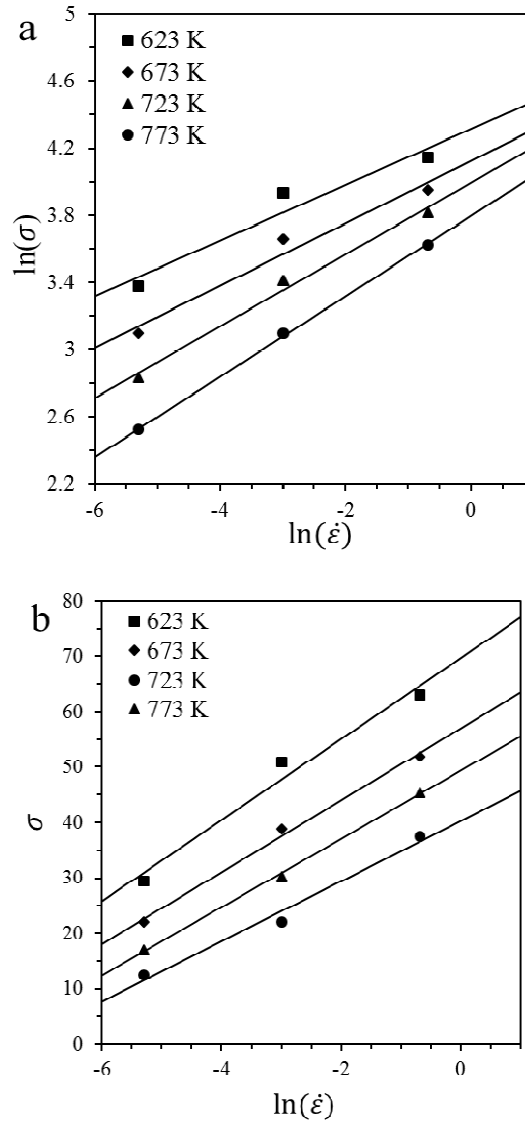


Figure 3: Evaluating the value of (a) n' by fitting $\ln\sigma_p - \ln\dot{\epsilon}$, and (b) β from the slope of straight lines $\sigma_p - \ln\dot{\epsilon}$.

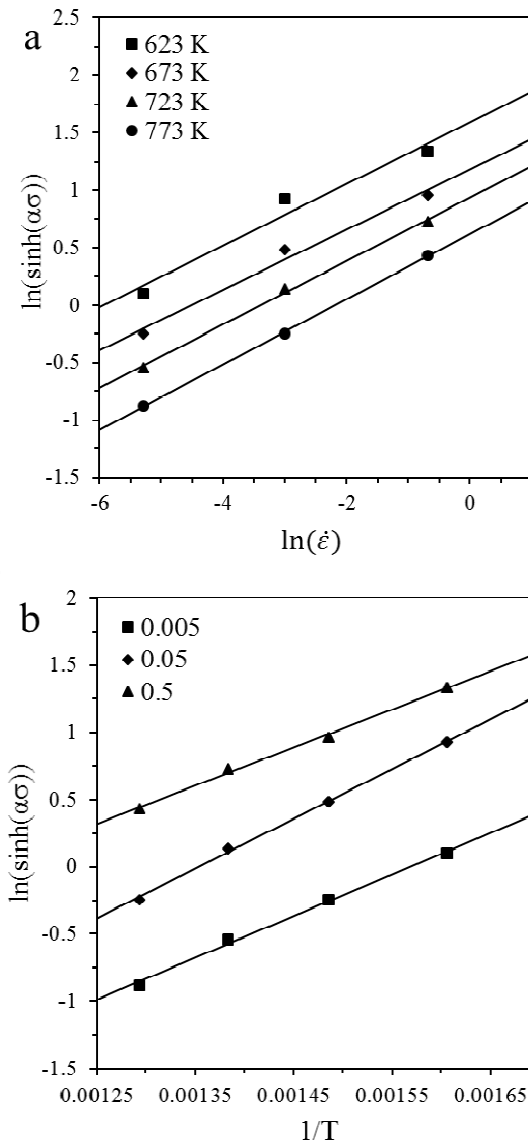


Figure 4: Evaluating the value of (a) n by fitting $\ln[\sinh(\alpha\sigma_p)] - \ln\dot{\epsilon}$ and (b) Q by fitting $\ln[\sinh(\alpha\sigma_p)] - 1/T$.

3.4 RELATIONSHIP BETWEEN PEAK STRESS AND ZENER-HOLOMON PARAMETER

The relation between peak stress (σ_p) and Z could be found according to Equations (5)-(7). Curves of $\ln Z$ versus σ_p , $\ln\sigma_p$, and $\ln[\sinh(\alpha\sigma_p)]$

are shown in Figures 5(a)–5(c), respectively, and the resultant regression equations with new constants are as below

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right) = 55.354 \times 10^5 \sigma_p^{5.067} \quad (14)$$

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right) = 15.58 \times 10^3 \exp(0.159\sigma_p) \quad (15)$$

$$Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right) = 47.544 \times 10^7 [\sinh(0.032\sigma)]^{3.665} \quad (16)$$

According to Figures 5(a)–6(c), the hyperbolic sine law has the highest correlation coefficient; therefore Equation (16) is suitable for analysis over a wide range of temperatures and strain rates, which is in agreement with this fact that hyperbolic sine relation is appropriate law for finding constitutive equation of Al-Cu-Mg-Pb aluminum alloy. The power law and exponential law also have a good fit; however, they are limited to low and high levels of stresses, respectively.

In summary, the peak stress of studied Al-Cu-Mg-Pb alloy under hot deformation condition used in this study may be expressed as Equation (16) as a result of rearrangement of Equation (16) with regard to the average of activation energy (Q).

$$\dot{\epsilon} = 47.544 \times 10^7 [\sinh(0.032\sigma)]^{3.665} \exp\left(-\frac{98.231 \times 10^3}{RT}\right) \quad (17)$$

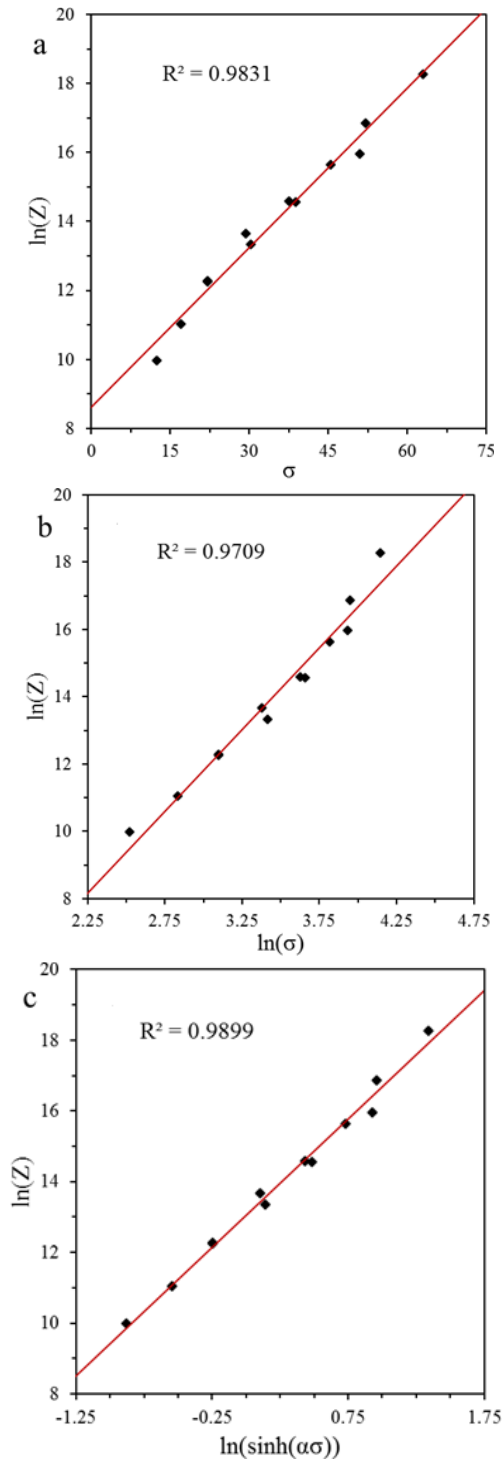


Figure 5: The variation of $\ln Z$ with (a) σ_p , (b) $\ln\sigma_p$, and (c) $\ln[\sinh(\alpha\sigma_p)]$ to obtain the consequence regression constant between the peak stress and Z

3.5 VERIFICATION OF THE DEVELOPED CONSTITUTIVE EQUATION

From the above-mentioned computation, by applying the determined material constants of the constitutive equation, the flow stress value can be calculated for strain rates between 0.005 and 0.5 s⁻¹ and temperatures between 623 and 773 K. In order to verify the accuracy of developed constitutive equation of Al-Cu-Mg-Pb aluminum alloy at high temperatures, a comparison between the experimental and predicted results was carried out as shown in Figures 6 and 7.

It could be observed that the predicted flow stress value from the developed constitutive equation that plotted against the experimental ones, which show a good correlation. The correlation coefficient between the experimental and the predicted flow stress is 99.3%, which indicates that the proposed deformation constitutive equation gives an accurate and precise estimate of the flow stress for commercially pure aluminum, and can be used to analyze the problems during hot metal forming process.

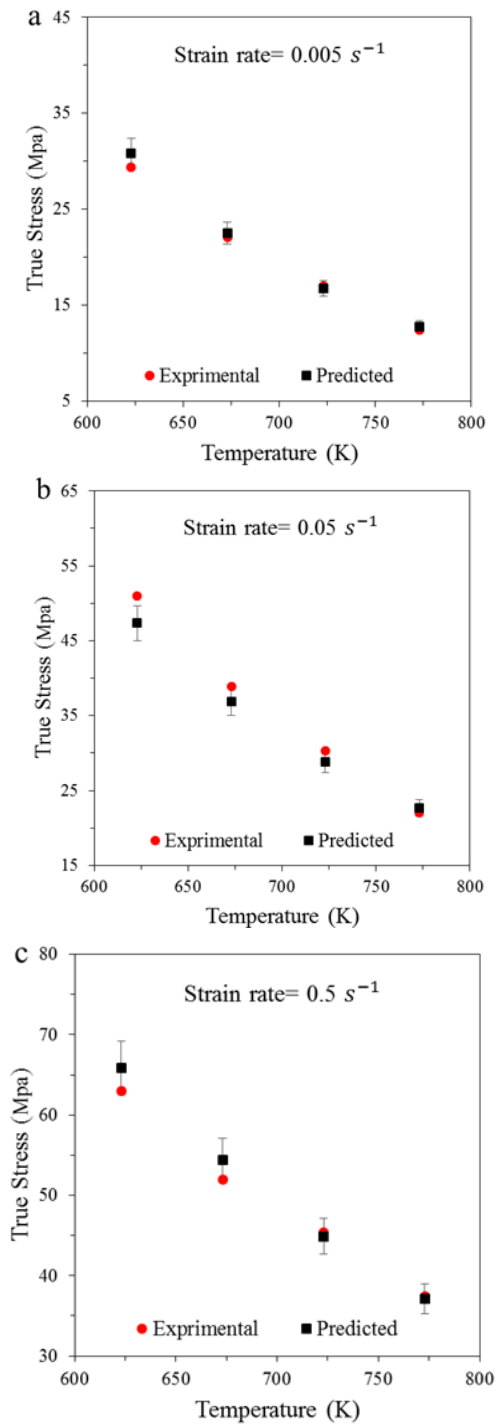


Figure 6: Correlation between the experimental and predicted flow stress from the hyperbolic sine relation at strain rate of (a) 0.005 s^{-1} , (b) 0.05 s^{-1} , and (c) 0.5 s^{-1} .

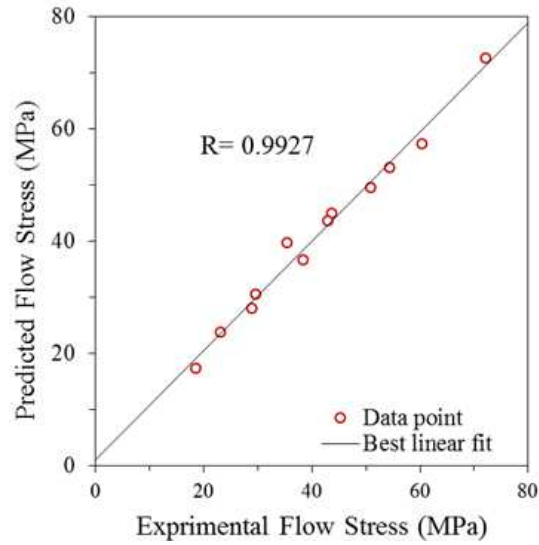


Figure 7: Correlation between the experimental and predicted flow stress data from the developed constitutive equation.

4.0 CONCLUSIONS

In this study, Constitutive analysis of Al-Cu-Mg-Pb aluminum alloy was carried out by isothermal hot compression tests in a wide range of temperatures and strain rates. Following are the conclusions:

- The flow stress decreases with increasing the deformation temperature and increases with increasing strain rate, which can be represented by Zener–Hollomon parameter in the power and exponential and sin hyperbolic type equation.
- The hyperbolic sine law has the highest correlation coefficient; therefore, the hyperbolic relation is suitable for analysis over a wide range of temperatures and strain rates, which is in agreement with this fact that hyperbolic sine relation is appropriate law for finding constitutive equation of Al-Cu-Mg-Pb aluminum alloy.
- The peak stress of studied Al-Cu-Mg-Pb aluminum alloy under hot deformation condition at a wide range of temperature (623-773 K) and strain rate (0.005–0.5 s⁻¹) used in this work may be expressed as

$$\dot{\epsilon} = 47.544 \times 10^7 [\sinh (0.032\sigma)]^{3.665} \exp\left(-\frac{98.231 \times 10^3}{RT}\right)$$

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