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Research Article

# Constitutive Modeling of 7075 Aluminum Alloy under the Hot Compression Condition

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ABSTRACT

The behavior of Al7075 during the hot compression in a wide range of temperatures, 623-773 K, and strain rates, 0.001-1 $s^{-1}$, were investigated in this paper. Moreover, using the standard Arrhenius constitutive models, a mathematical equation was proposed for predicting the flow stress, and then the accuracy of the model was examined using standard verification methods. The increasing of temperature and strain rate, respectively, have a reverse and direct effect on the flow stress, which can be expressed using the Zener-Hollomon parameter with the activation energy of 304 kJ/mol. Since the potential dependence of the constants in the model has not been considered for any parameter, the accuracy of the standard model is low. It was found that the values of these constants depend on the strain, so for each of the constants, a relation was obtained in terms of strain to express this relation properly. The modified model not only precisely predicts the flow stress but also provides higher accuracy in predicting the trend of variation of stress due to the influence of metallurgical evolutions occurring during the process of hot deformation, such as dynamic recrystallization or softening and hardening.



## 1. Introduction

Aluminum 7xxx alloy series are very suitable for the construction of aircraft and aerospace structures due to special properties such as good strength, high corrosion resistance, and high tensile strength [1-3]. In metal forming processes such as extrusion, forging, and rolling the workability is an important parameter that can be developed by optimizing parameters of the forming process. Determining the optimal parameters of the forming process in a specific condition depends on the complete understanding of the hot-deformation behavior of the alloy. There is also a great deal of interest in modeling of production processes to ensure that the process is properly performed, which requires the availability of a precise mathematical model to define the behavior of the material (flow stress) in terms of parameters such as temperature, strain, and strain rate. Therefore, studying the behavior of the hot forming of alloys and attempting to extract the mathematical model for its behavior is necessary and valuable.

To this day, the hot-deformation behavior of the 7xxx series of aluminum alloys has been studied by several researchers. The deformation behavior of alloy 7150 has been studied at high temperatures by Jin et al. [4]. They accurately interpreted the flow stress during the process and linked the process of increasing or decreasing the stress to the metallurgical processes that occurred during the process, and used the Zener-Hollomon parameter. Rokni et al. proposed a constitutive equation for Al7075 during hot-deformation

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by employing a standard exponent-type equation [3]. Lin et al. explored the material flow behavior and microstructural evolution of Al7075 during the hot-forming process. Wang et al. investigated the compressive deformation of quenched Al7005 alloy and proposed an exponent-type constitutive equation [5], and then studied the instability domain of the alloy during the deformation process. Bobbili et al. proposed a constitutive equation to predict the flow stress of Al7017 at a high strain rate [6]. Chen et al. presented an equation to describe the behavior of the 7005 aluminum alloy deformation during the extrusion process, in which they performed experiments at strain rates higher than 1 $s^{-1}$ [7]. Lin et al. studied the microstructural evolutions of the 7075 aluminum alloy during deformation under pressure at high temperatures and related how stress changes with microstructural evolution [2]. Zhang et al. have studied the effect of initial microstructure on the hot deformation process of 7000 aluminum alloys series and its effect on microstructural changes during the high-temperature deformation process such as dynamic recrystallization (DRX) and dynamic recovery [8]. They have also extracted the process map of this alloy series by presenting a model based on the standard Arrhenius model [9]. Liu et al. studied the hot deformation process of 7085 aluminum alloy and investigated the microstructural changes and dynamic recrystallization using the Zener-Hollomon parameter value [10]. Rajamuthamilselvan et al. have studied in detail the microstructural evolutions of Stir cast 7075 alloy during quasi-static deformation at high temperatures [11]. Ke et al. have studied the microstructural changes and the hardening and recovery mechanisms of 7020 aluminum alloy during hot deformation and have also extracted the processing maps of alloys [12].

In this research, the hot deformation of Al7075 alloy was studied with the aim of extracting a mathematical model to define the hot deformation of the alloy. For this purpose, a series of hot compression tests were performed in a wide range of temperatures (623-773 K) and strain rates (0.001-1 $s^{-1}$) on this alloy. A model was extracted using the Arrhenius standard form. To increase the accuracy of the extracted model, a new model was obtained in which the dependence of the constants on the strain were also taken into consideration.

## 2. Experimental Procedure

In this study, the 7075 aluminum rod, which is cold extruded, was utilized. The chemical composition (wt.%) of the materials is as follows: 6.1 Zn, 2.3 Mg, 2.1 Cu, 0.12 Fe, 0.1 Si, 0.09 Zr, with the balance aluminum. The cylindrical shape test specimens with the size of Φ8x12 mm were cut from the rod and prepared using the machining process [13]. To homogenize the microstructure of the samples and to eliminate the effect of the preparation processes (especially the residual stress), samples were solutionized at 550°C for 4 hours and quenched in water at 50- 60°C [14]. The specimen's microstructure before the test is shown in Fig. 1. The grains almost had an average diameter of about 300 µm, and without any specific orientation in the structure.

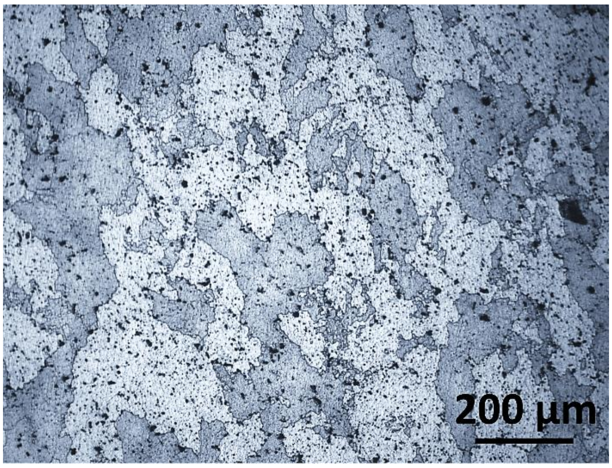


**Fig. 1.** The primary microstructure of samples.

The tests were performed using a SANTAM hot pressing machine at four different temperatures (623, 673, 723, and 773 K) and four different strain rates (0.001, 0.01, 0.1, and 1 $s^{-1}$). There was friction between the anvil and the sample, which could prevent the uniform deformation during the hot deformation process. In this research, a combination of graphite powder and refractory grease has been used as a lubricant. Moreover, to eliminate the effect of friction parameter on the true stress-strain diagrams, the shear coefficient of friction was calculated by ring compression test, and the true stress has been modified by that [15]. The temperature of the specimens is increased at the rate of 10 K/s by the electric furnace. After reaching the desired temperature, to ensure that the whole specimen has the same temperature, it was maintained at this temperature for 5 minutes before going through the compression process.

The samples were compressed up to 40% of the original height and then quickly cooled till the microstructure remained the most similar to the end of the compression process. In the studies of the hot-deformation process of materials, finding optimum parameters to improve the workability is important, and the deformation without failure and cracking, is one of the determining factors. In the experiments, all specimens were examined for cracks, and it was observed that there were no traces of them.

## 3. Results and Discussion

The modified true stress-true strain curves, which are obtained from the hot compression test of the specimens, are shown in Fig. 2. Generally, a similar trend is observed in most of the diagrams, and three parts consisting of work-hardening, recovery, and steady-state are observed in most of the stress-strain curves. The process of changing the stress starts with a fast increase, which is due to increasing dislocation density during the process, and work-hardening [16]. It should be noted that at the same time as the stress increases, due to work-hardening, the softening process is also going to reduce the amount of stress, but first, the work-hardening is dominant. In the following, when the stress reaches the maximum value it was slightly decreased because of the overpowering of the softening due to the reorganization of dislocations. In general, the increase in stress corresponds to the work hardening phenomenon caused by the rapid increase of dislocation density, and its reduction is related to the dynamic softening that tends to occur with the proceeding of hot deformation. Finally, the stress tends to be stable because the production and reorganization of dislocations lead to dynamic equilibrium. It should be noted that the strain range in which the model is extracted is limited to strains less than 0.5.

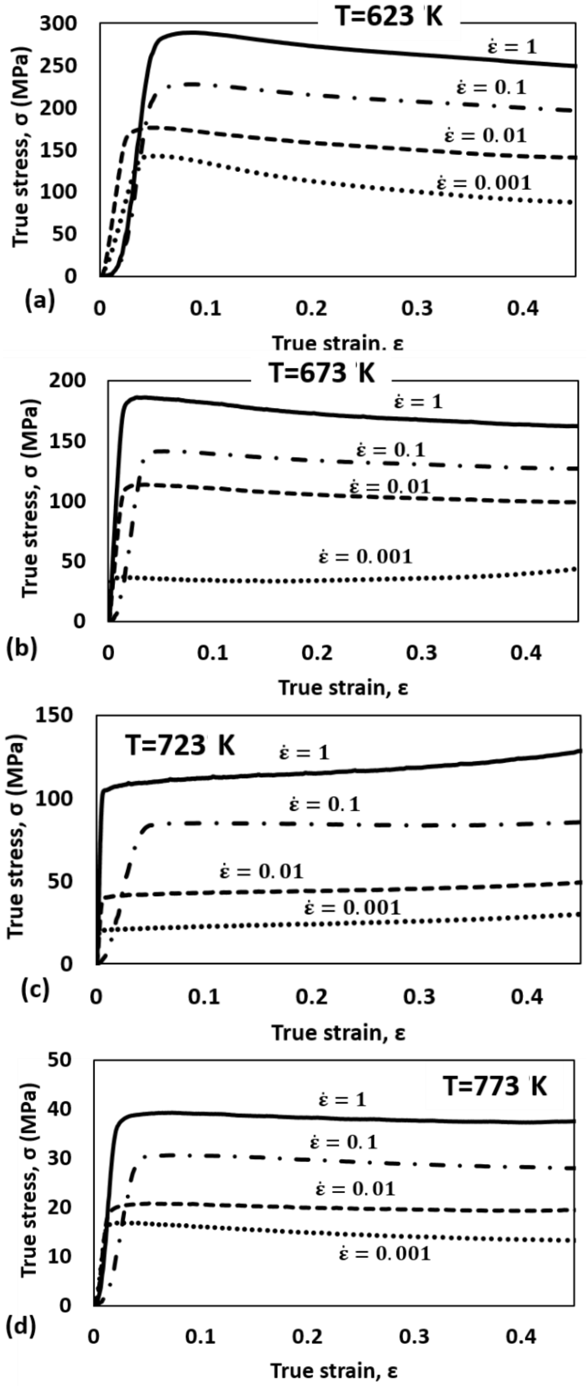


**Fig. 2.** True stress-strain curves: (a) 623 K, (b) 673 K, (c) 723 K and (d) 773 K.

The bar chart of the $\sigma_{max} - temperature$ and $\sigma_{max} - \dot{\varepsilon}$ are shown in Fig. 3. The results of the statistical analysis of the maximum stress variation in terms of strain rate and temperature reveal that the effect of temperature and strain rate on the maximum stress variation is significant (P- Value<0.003). Additionally, according to ANOVA statistical analysis, the effects of temperature on flow stress change were more significant than the strain rate.

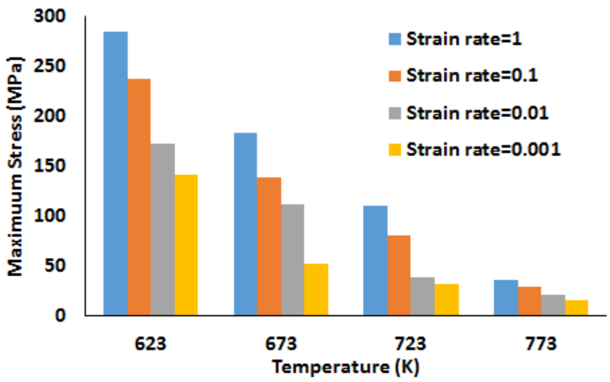


**Fig. 3.** The maximum stress variation in terms of temperature and strain rate.

## 4. Standard Arrhenius Model

The constitutive models are commonly used to explain the deformation process of alloys at high temperatures. The constitutive equations have a critical and decisive role in analyzing and, in particular, numerical modeling of forming and machining processes. Generally, The power law, Eq. (1), and the exponent-type equation, Eq. (2), break at a high stress and a low stress, respectively [16-18], which are displayed as follows:

$$\dot{\varepsilon} = A_1 \sigma^{n_1} exp\left(-\frac{Q}{RT}\right) \quad (1)$$

$$\dot{\varepsilon} = A_2\, exp(\beta\sigma)\, exp\left(-\frac{Q}{RT}\right) \quad (2)$$

The Arrhenius equation is one of the widely used equations [19], a hyperbolic sinus equation, describes the flow stress of materials in a wide range of strains and temperatures. In addition, the effect of temperature and strain rate on hot deformation in the form of mathematical equations can be described by using the Zener-Hollomon parameter (Z) [18]. In the analysis of material behavior during deformation at high temperatures, the activation energy of deformation (Q) is used, which is the process controller in those conditions [18]. In the Arrhenius equation, the flow stress, with the help of the Zener-Hollomon parameter, is correlated to the strain, strain rate, and temperature, which are as follows:

$$\sigma = \frac{1}{\alpha} ln\left\{\left(\frac{Z}{A}\right)^{1/n} + \left[\left(\frac{Z}{A}\right)^{2/n} + 1\right]^{1/2}\right\} \quad (3)$$

$$Z = \dot{\varepsilon}\, exp\left(\frac{Q}{RT}\right) = A[sinh(\alpha\sigma)]^n \quad (4)$$

By considering the natural logarithm of the equations (1) and (2), the following relations are obtained:

$$ln(\dot{\varepsilon}) = ln(A_1) + n_1 ln(\sigma) - \frac{Q}{RT} \quad (5)$$

$$ln(\dot{\varepsilon}) = ln(A_2) + \beta\sigma - \frac{Q}{RT} \quad (6)$$

The $ln(\dot{\varepsilon}) - ln(\sigma)$ and $ln(\dot{\varepsilon}) - \sigma$ curves are plotted in Fig. 4 using the true stress and strain measured values to understand the relationship between them. Hence, as shown in Fig. 4, natural logarithmic diagrams include a group of straight lines, the Zener-Hollomon parameter, which is an exponential function that can be used to describe the hot deformation behavior. Moreover, according to equations 5 and 6, the constants $n_1$ and $\beta$ are obtained from the slope of the lines which are fitted on the data with acceptable accuracy (correlation coefficient, R = 0.95). Also, the value of the $\alpha$ parameter is calculated using the values $n_1$ and $\beta$.

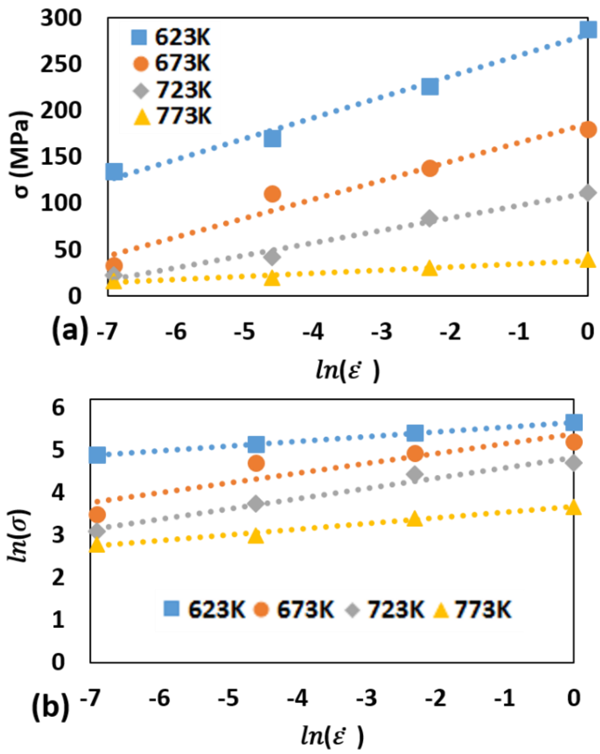


**Fig. 4.** The relation of a) $\sigma - ln(\dot{\varepsilon})$ and b) $ln(\sigma) - ln(\dot{\varepsilon})$ curves.

By combining equations 3 and 4, equation (7) is obtained to calculate the energy of activation:

$$Q = R\left[\frac{\partial ln(\dot{\varepsilon})}{\partial ln[sinh(\alpha\sigma)]}\right]_T \left[\frac{\partial ln[sinh(\alpha\sigma)]}{\partial(1/T)}\right]_{\dot{\varepsilon}} \quad (7)$$

To the right of equation (7), the first and second sentences are respectively equal to the slope of the $ln[sinh(\alpha\sigma)] - ln(\dot{\varepsilon})$ at constant temperature and $ln[sinh(\alpha\sigma)] - {}^{1}/_{T}$ at constant strain rate, which are shown in Fig. 5. The deformation activation energy can be a parameter to understand the type of the main softening mechanism. When it is close to the self-diffusion activation energy, the main softening mechanism is dynamic recovery [20]. While the deformation activation energy is much larger than the self-diffusion activation energy, the main softening mechanism is dynamic recrystallization [20]. The self-diffusion activation energy for pure aluminum is 142 kJ/mol [4]. The calculated deformation activation energy of 7075 alloy is 304.1 kJ/mol, which is much higher than the self-diffusion activation energy for pure aluminum. Therefore, it can be concluded that the main softening mechanism is dynamic recrystallization.

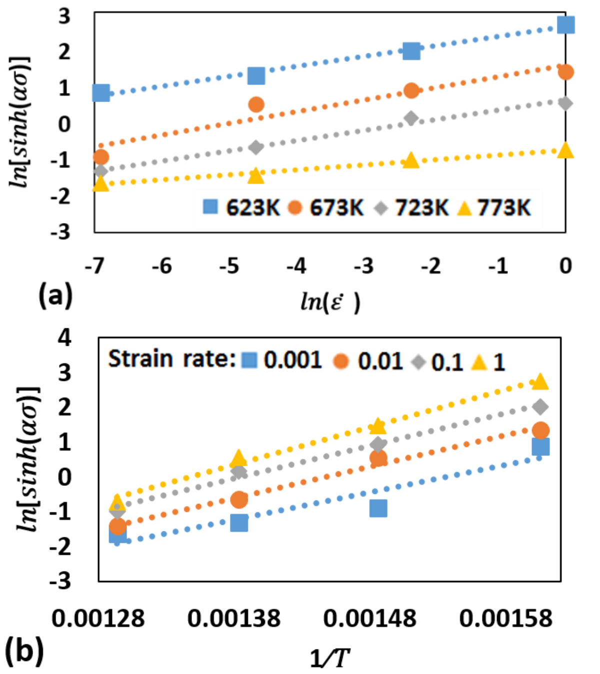

**Fig. 5.** The relation of a) $ln[sinh(\alpha\sigma)] - ln(\dot{\varepsilon})$ and b) $ln[sinh(\alpha\sigma)] - {}^{1}/_{T}$ .

The coefficients n and A in equation (4) are calculated from equation (8) obtained by the logarithm of equation (4). By plotting $ln(Z) - ln[sinh(\alpha\sigma)]$ and fitting a straight on it (correlation coefficient is R = 0.93), the coefficients n and A are respectively the slope and intercept of this line, as shown in Fig. 6.

$$ln(Z) = ln(A) + n\, ln[sinh(\alpha\sigma)] \quad (8)$$

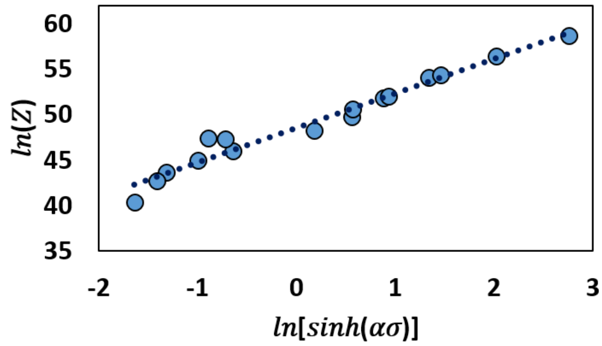

**Fig. 6.** The relation of $ln(Z) - ln[sinh(\alpha\sigma)]$.

All calculated coefficients are given in table 1. Finally, the equation describing the relationship between flow stress and strain, strain stress, and the temperature is as follows:

$$\sigma = \frac{1}{0.012} ln\left\{\left(\frac{Z}{1.228\times10^{21}}\right)^{0.2639} + \left[\left(\frac{Z}{1.228\times10^{21}}\right)^{0.5277} + 1\right]^{1/2}\right\} \quad (9)$$

**Table 1.** The Arrhenius model coefficients

| $\beta$ $(MPa^{-1})$ | $n_1$ | $\alpha$ $(MPa^{-1})$ | Q $(kJ/mol)$ | $ln(A)$ | n |
|---|---|---|---|---|---|
| 14.9 | 0.18 | 0.012036607 | 304.1 | 48.56 | 3.79 |

## 5. Strain compensated Arrhenius model

Under the influence of metallurgical evolutions occurring during the process of hot deformation, such as dynamic recrystallization, flow stress usually changes. Therefore, a model that is suggested to describe the behavior of the material should also be able to describe the metallurgical evolutions. Since the constants of the standard Arrhenius ($\alpha$, n, Q, and A) are all calculated in the specific strain (reference strain), the probability of strain influence on them has not been investigated. This is while the strain's influence on Q and other constants of the Arrhenius equation are significant. Consequently, the Arrhenius model must be modified to predict the flow stress accurately during hot deformation, to examine how the constants of the Arrhenius model depend on the strain, and extract the relation as a mathematical equation of strain.

In this study, the material constants in the strain range of 0.05-0.75 were calculated by using the method which was described in the previous section, and the results are plotted in Fig. 7. The graphs indicated that each of the constants significantly change with the strain variation, and attempts to extract the mathematical equations that express this relation is worthwhile. To derive the best mathematical relationship between each of the constants and the strain, the curve fitting technique has been used. The best curve has been chosen by setting the higher correlation coefficient. All results are presented in Table 2, and the fitted curves are shown in Fig. 7 by red dots. Therefore, the material constants can be calculated using the equations extracted in Table 2 for each strain in the range 0.05-0.75, and then the flow stress at each strain, the temperature, and strain rate can be calculated by the equations (3) and (4).

## 6. Analysis of the accuracy of the proposed models

In the analysis, which is presented in detail in the previous sections, models were proposed to describe the behavior of the flow stress of Al 7075 aluminum during hot deformation based on standard and modified Arrhenius models. In the improved model, the constants are a function of the strain, and the corresponding function is determined. To examine the accuracy of the model, the flow stress values were calculated using the presented models in the strain range of 0.1-0. 5 and with distances of 0.05 and compared with the stresses obtained from the experiments. The calculated and measured values are plotted and compared in Fig. 8, in which the dashed red line is the ideal state and represents the perfect match between the results. As shown in Fig. 8 (a) and (b), the density of points in the modified model is closer to the ideal line, which indicates a better accuracy of the model, meaning it can predict the alloy's behavior more accurately than the standard model.

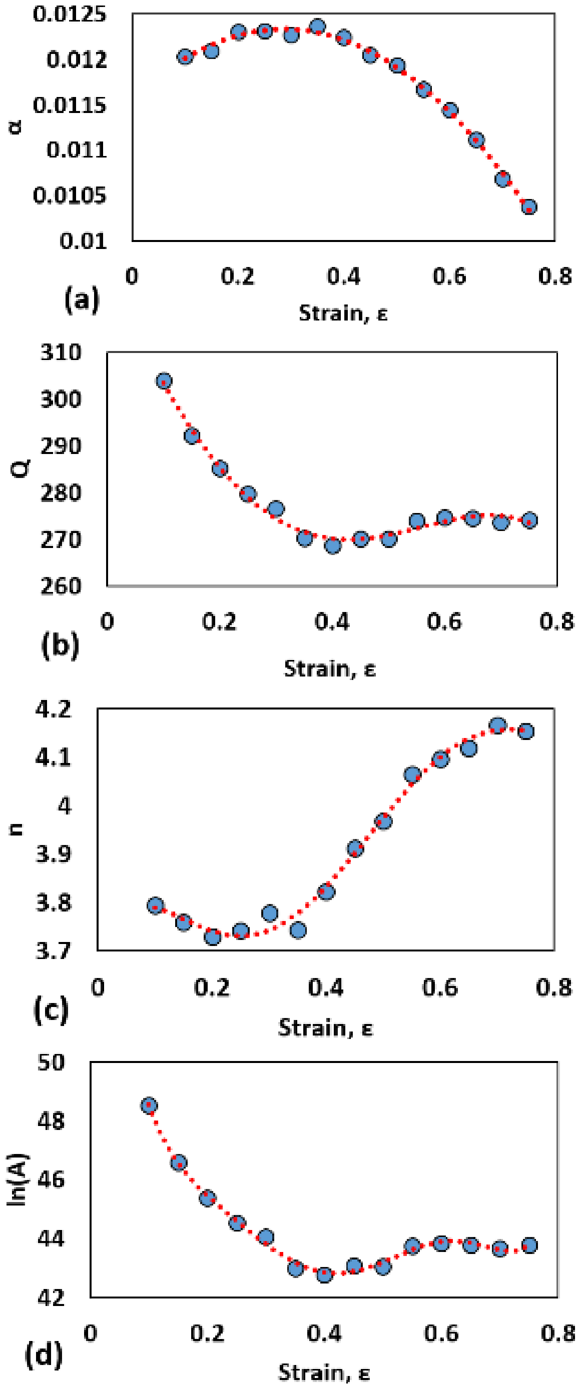


**Fig. 7.** Arrhenius Standard Model Constants Changes with strain: a) α, b) Q, c) n and d) $ln(A)$.

Table 2. The extracted relation for the constants of the Arrhenius equation.

| Parameter | Equation type | Formula | Correlation factor |
|---|---|---|---|
| **α** | Quadratic polynomial | $-0.0093\varepsilon^2 + 0.0054\varepsilon + 0.0116$ | 0.99 |
| **Q** | Fourth degree polynomial | $-464.48\varepsilon^4 + 373.58\varepsilon^3 + 251.42\varepsilon^2 - 275.67\varepsilon + 328.23$ | 0.99 |
| **n** | Fifth degree polynomial | $37.282\varepsilon^5 - 87.409\varepsilon^4 + 69.601\varepsilon^3 - 20.758\varepsilon^2 + 2.0662\varepsilon + 3.7294$ | 0.99 |
| $\boldsymbol{ln(A)}$ | Sixth degree polynomial | $5749.5\varepsilon^6 - 14528\varepsilon^5 + 14317\varepsilon^4 - 7012.5\varepsilon^3 + 1835.2\varepsilon^2 - 263.97\varepsilon + 62.33$ | 0.99 |

To examine the accuracy quantitatively, the average absolute relative error (AARE) (considered to verify the possibility of forecasting of the models as an unbiased statistical parameter) and correlation coefficient (R) (reflects the strength of the linear relationship of the experimental-predicted data) are used. All of the data that are plotted in Fig. 8 are used to calculate the AARE and R, and the results are shown in Table 3. Although the accuracy of both models in determining the flow stress of the material is appropriate during the hot-deformation process, the predicted results of the improved Arrhenius model are more accurate, and its error rate is about 50% lower. The predicted results and the measured values of stress under different conditions are plotted in Fig. 9 and are compared to each other. In this comparison the solid points represent the values predicted by the strain compensated Arrhenius model. The observation of the results shows that the proposed model has acceptable accuracy in not only predicting the amount but also the trend of variations in flow stress.

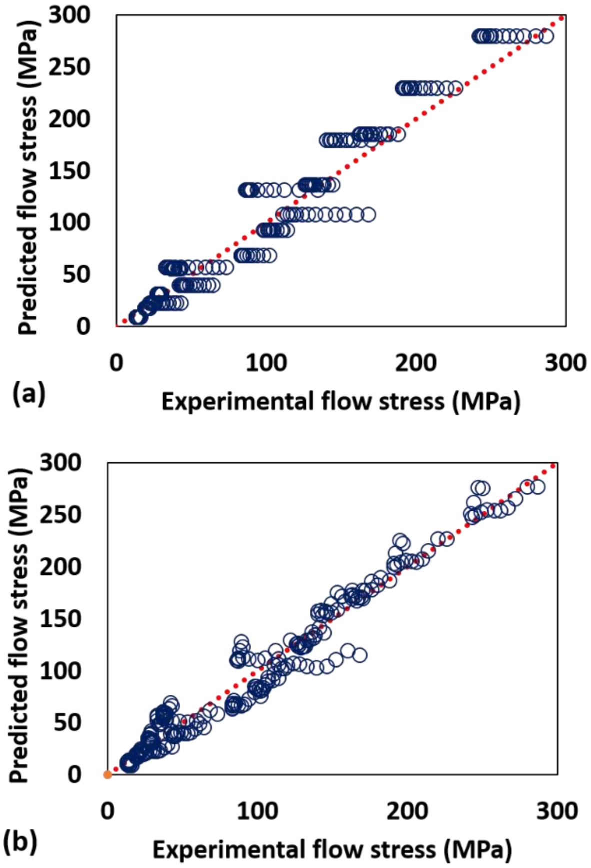


**Fig. 8.** Matching measured and predicted values of flow stress by models: a) Arrhenius and b) Strain compensated Arrhenius.

**Table 3.** Accuracy analysis of models based on R and AARE.

| Proposed model | R | AARE (%) |
|---|---|---|
| **Arrhenius** | 0.97 | 17 |
| **Strain compensated Arrhenius** | 0.98 | 8 |

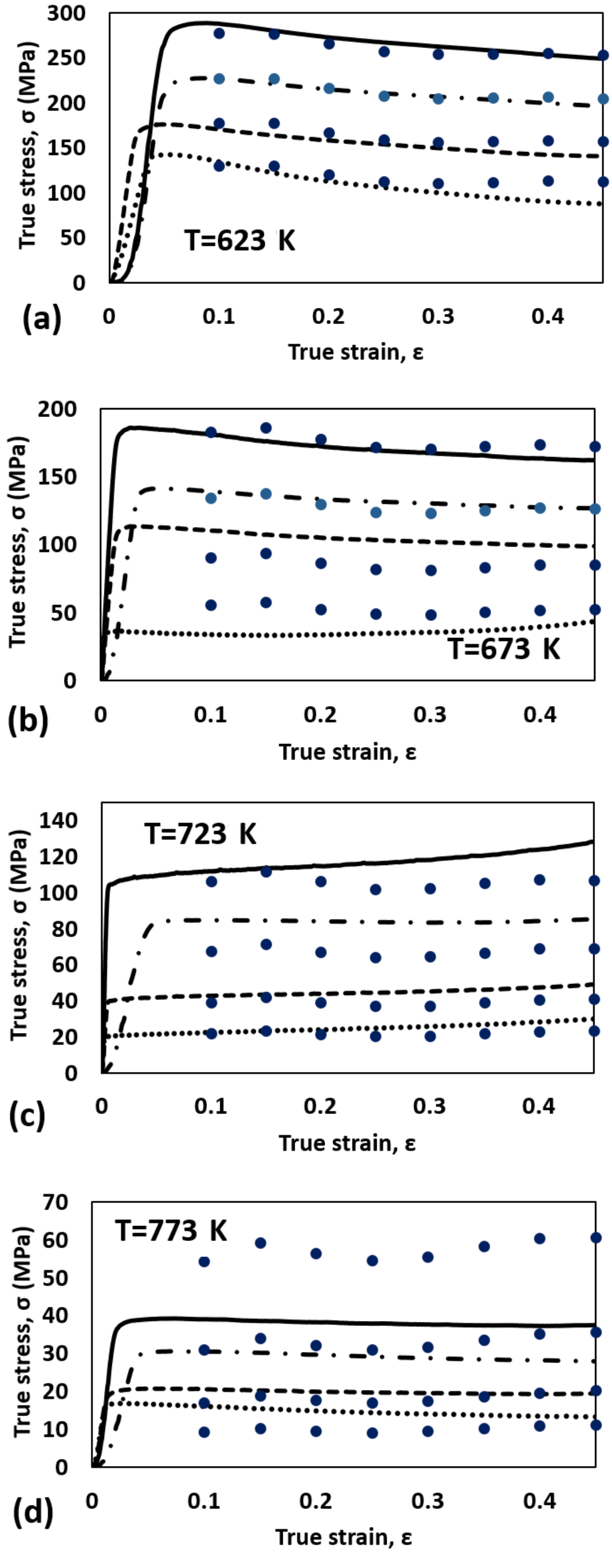


**Fig. 9.** Adaptation between predicted flow stresses by Strain compensated Arrhenius model and measured values.

## 7. Conclusion

Using a set of experiments, in this research, the hot-compression behavior of Al7075 alloy has been studied. Furthermore, an equation has been derived based on the Arrhenius model that can describe the flow stress of this alloy in the specific range of strain, the strain rate, and the temperature. Since it was found that the constants of the Arrhenius equation depend on the strain, the standard form of the model was modified by deriving a strain-related equation for each of the constants. The obtained results in this research can be summarized as follows:

1- Flow stress is significantly influenced by the strain rate and temperature, but the effect of the temperature is higher. Because of the increased rate of dislocation generation, the higher strain rate increases the amount of flow stress, while the higher temperature reduces its amount due to the reverse effect it has. It also helps rebuild the microstructure and reduce the dislocation density.

2- Due to the inability to involve the effect of strain on flow stress at a constant temperature and strain rate the standard Arrhenius model has a defect and is particularly ineffective in predicting the trend of stress variations. This is while the modified Arrhenius model has significantly higher accuracy and can further predict the trend of increasing stress (due to increased dislocation) and its reduction (due to the recovery). The accuracy of the models decreases by being distanced from the reference conditions, and the lowest accuracy occurs at the highest temperature and strain rate.

3- According to the analysis of the proposed Arrhenius model, at the strain of 0.5, the value of the activation deformation energy, Q, is estimated at about 304 kJ/mol. Because of much more activation energy compared to self-diffusion for pure aluminum (140 kJ/mol), the main mechanism used during the deformation is dynamic recrystallization.

4- It was determined that although the accuracy of the standard and specially modified Arrhenius models in predicting the flow stress of the materials is appropriate during the hot-deformation process, the proposed results of the modified Arrhenius model have a 50% lower error than the standard one.

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