Constitutive modeling of creep properties of Aluminum 6061 Alloy

Shivakumar S.Pa, Sharan A.Sb, K.sadashivappa c

1Department of Automobile Engineering, S.J.M.I.T., Chitradurga-
2Department of Mechanical Engineering, B.I. E.T., Davangere-577005
3Department of Mechanical Engineering, B.I. E.T., Davangere-577005

E-mail: shiv180@gmail.com

Abstract.
A novel mathematical model is presented for determination of creep behavior of Aluminum 6061 alloy subjected to constant-stress uniaxial tensile creep experiment. The methodology employed to obtain the constants is by conducting experiments at the temperature range of 573 K to 673 K (300 oC to 400oC) at different stress intervals 64.5 MPa and 98.1 MPa. The creep properties such as creep strain rate for all three stages, rupture time, rupture stress, rupture strain and percentage elongation of specimen are calculated. Depending on the temperature and the applied stress, exhibits significant effects on the strain rate and activation energy. The results show that the creep behaviors of the studied aluminum alloy strongly depend on the creep temperature, external stress, and creep time.

Keywords: Aluminum 6061, uniaxial tensile creep, Arrhenius equation

1.Introduction
Aluminum casting alloys have low density, high corrosion resistance and good ductility. They are also easily cast, fabricated, formed, machined, and welded components. Aluminum 6061 offers for a wide range of properties that aids in accurate design and fabrication of components for specific applications. Hence they feature in a wide range of products such as aircraft structures, ships and military equipment’s, automobile and its components. The major benefits of aluminum 6061 alloys are described as their low weight, low density, and high specific strength, good stiffness, large corrosion resistance, good strength compared to other metallic alloy [1-3]. The chemical composition is shown in the table.1. The major constituents are magnesium, silicon and iron. These constituents significantly influence on the mechanical properties. The composition also possesses transition metals such as Fe and Mn. During casting of 6061 aluminium alloys a wide variety of Fe-containing intermetallic such as Al-Fe, Al-Fe-Si and Al-Fe-Mn-Si phases are formed between the aluminium dendrites. Aluminum 6061 achieves the peak of strength in the T6 temper by being heated, close to 175°C for multiple hours [4]. Generally, aluminium is considered to have distinct disadvantages when it comes to fire resistance. Its need for fire protection is more pronounced in comparison to steel, due to its higher thermal conductivity (>100 W/m²K) and lower melting point (560–660 °C) [5]

Creep deformation is unavoidable in cast parts that experience stress at elevated temperature resulting in gradual stress relaxation and strain accumulation results in early failure of components. Evident confirmations from the industry and research institutions show that a new set of creep damage constitutive equations is required to be developed to describe the creep damage behavior and rupture lifetime [6-8]. Suitable modeling tools and databases are essential for satisfactory prediction of the
creep behaviour. There are several creep models available, but generation of reliable creep databases is costly and time consuming. Modeling of the creep behaviour of aluminum alloy 2024-T3 has been made in [8], using the h-projection’’ method for temperatures range of 593 K to 753 K and strain rates ranging from 0.001 to 0.1 s-1. The h-projection’’ method has been used to describe the creep of other aluminum alloys. A. Khamei et al. [10] have obtained a creep model severe plastic deformation, of Aluminum 6061 alloy which is treated by using equal-channel angular pressing and then followed by cold rolling. Mohammad et al [3], has given an empirical model to calculate the activation energy of the creep process and given some of the basic mechanisms that play major role in both creep process and time-depending plastic deformation characterization. Caijun et al. [11 ] determined the uniaxial power-law creep parameters α and n in the equation \( \dot{\varepsilon} = \alpha \sigma^n \) by employing the data obtained by conducting indentation tests using a pyramidal indenter. Maria et al. [12], in their work, gives various physical mechanisms that underlays the creep failure within metals are revisited and then the frameworks in order to model the high temperature creep behavior are debated Kowalewski et al. [13] modelled a metallic material creep unified constitutive model, used to describe the creep deformation behaviours of the material from the initial stage to the third stage of creep induced by dislocation hardening, nucleation at grain boundary holes. Ho et al. [14] developed a set of constitutive equations, which models primary and secondary creep and precipitate nucleation and growth for AA7010 aged at 150 °C. Huang et al. [15] used a set of creep damage constitutive equations, to describe creep damage, which is related to the over aged condition, and models failure at the tertiary creep stage.

2. Constitutive model

Constitutive equations that relate the flow stress of a material with a known initial microstructure to the strain, strain rate, and temperature of deformation are an essential input for computer modelling thermomechanical properties. The high temperature deformation activities of alloys in the course of hot compression and hot tension tests can be defined by most extensively used Arrhenius-type equation [1, 2]

\[
\dot{\varepsilon} = A [\sinh(\alpha \sigma_f)]^n \exp(\frac{-Q}{R \times T})
\]  

(1)

where n is the stress exponent, \( \beta \) and \( \alpha \) are the material constants, Q is the activation energy which is related to high temperature deformation mechanisms which occurs during hot forming (J mol\(^{-1}\)), A is pre-factor of pre-exponential factor, \( \sigma_f \) is the flow stress or instantaneous stress (MPa), \( \dot{\varepsilon} \) is the strain rate (s-1). (Refer appendix for calculations), The Zener–Hollomon parameter which relates between strain rate and temperature during high temperature deformation of material is given by:

\[
Z = \dot{\varepsilon} \exp(\frac{Q}{R \times T}) = A [\sinh(\alpha \sigma_f)]^n
\]

(2)

The dependence of strain rate and temperature on flow stress or instantaneous stress, taking into account the definition of hyperbolic sinusoidal law is usually given by:

\[
\sigma_f = (\frac{1}{a}) \ln \left( \frac{Z}{A} \right)^{\frac{1}{n}} + \sqrt{\left( \frac{Z}{A} \right)^{\frac{2}{n}} + 1}
\]

(3)
The gradients of the lines plotted in ln(Instantaneous strain rate) \( (s^{-1}) \) against ln(Instantaneous stress) (MPa) gives the value of stress exponent \( n \) and the value of material constant \( \beta \) can be calculated by the gradients of lines plotted in ln(Instantaneous strain rate) \( (s^{-1}) \) against Instantaneous stress (MPa). By using the stress exponent \( n \) and the material constant \( \beta \) another parameter \( \alpha \) can be calculated as:

\[
\alpha = \frac{\beta}{n} \quad (4)
\]

Unit of \( \alpha \) is MPa\(^{-1}\). The activation energy \( (Q) \) can be obtained by using a parameter called Larson–Miller parameter; Larson–Miller parameter [3] is a useful parameter to estimate the creep activation energy of materials. Larson–Miller parameter can be derived from Dorn relation:

\[
\varepsilon = A\sigma^n \exp\left(-\frac{Q}{RT}\right) \quad (5)
\]

where \( n \) is the stress exponent, \( \alpha \) is the material constant, \( A \) is pre-factor of pre-exponential factor, \( \sigma \) is the applied stress (MPa), \( Q \) is the activation energy which is related to high temperature deformation mechanisms which occurs during hot forming (J mol\(^{-1}\)), \( T \) is the absolute temperature (K), \( R \) is the universal gas constant (8.314 J mol\(^{-1}\) K\(^{-1}\)), and \( \varepsilon \) is the strain rate (s\(^{-1}\)). Then, the rupture time is given by, phenomenologic

\[
t_r = \text{constant} \times \sigma^{-n} \times \exp\left(\frac{Q}{RT}\right) \quad (6)
\]

Taking logarithms from both sides, results in:

\[
\log(t_r) = \log(\text{constant}) - n\log(\sigma) + \frac{Q}{2.3R} \times \frac{1}{T} \quad (7)
\]

\[
T \times \log(t_r) = T \times [\log(\text{constant})] - n\log(\sigma) + \frac{Q}{2.3R} = T \times (\log c) + \frac{Q}{2.3R} \quad (8)
\]

Then by a given stress \( \sigma \) (constant value):

\[
T \times [\log(t_r) - \log c] = \frac{Q}{2.3R} \quad (9)
\]

The Larson–Miller parameter is given by:

\[
P_{LM} = \frac{Q}{2.3R} = T \times [\log(t_r) + C] \quad (10)
\]

Where \( t_r \) is the rupture time in hours, \( R \) is the universal gas constant (8.314 J mol\(^{-1}\) K\(^{-1}\)) and \( T \) is the absolute temperature in Kelvin (K). For Aluminum 6061 we are going to take the parameter \( C = 14 \). The unit of activation energy is J mol\(^{-1}\).
\[ Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = A \times \left[ \sinh(\alpha\sigma_f) \right] \]

The pre-factor or pre-exponential factor \( A \) has the unit (s\(^{-1}\)). The above values of stress exponent \( n \), material parameter \( \alpha \), activation energy \( Q \) and the pre-factor or pre-exponential factor \( A \) can be substituted in Arrhenius type equation to obtain analytical creep strain rate.

\[ \dot{\varepsilon} = A \left[ \sin(\alpha\sigma_f) \right] \times \exp\left(\frac{-Q}{R \times T}\right) \]

The unit of creep strain rate is s\(^{-1}\). But the strain rate \( \varepsilon \) is change in strain \( \delta \varepsilon \). Analytical creep strain value at 20 seconds is.

\[ \varepsilon_{20} = \delta \varepsilon + \varepsilon_0 \]

Same above procedure is used to obtain analytical creep strain at different time intervals for each combination of applied stress and applied temperature. After getting analytical creep strain values for all the time intervals, we are going to get analytical creep curve and finally both the experimental creep curve and analytical creep curve can be compared for different combination of applied stress and temperature.

3. Testing

The dimensions for the specimen used have been given below. As mentioned earlier, the specimens prepared were made out of an Aluminum 6061-T6 alloy. Based on ASTM E-139 specimens were prepared to conduct the experiment.

![Figure 1 Specimen dimensions](image)

Creep phenomenon is a time dependent plasticity of materials at a constant applied stress level and at a higher temperature, which has to be greater than approximately \( 0.4T_m \) to \( 0.7T_m \) for the creep phenomenon to take place, where \( T_m \) is melting point of the material. The creep phenomenon is a temperature-dependent process because the dimensional changes that take place for an applied stress level increases considerably when the temperature is raised [3]. The testing procedure is discussed below.

- First, the specimen was fitted and aligned in the middle of the furnace and one additional thermocouple was wired in the middle of the specimen gauge length.
- The furnace was closed and the heating was switched on. Thermal cotton was used to cover the top and bottom of the furnace to reduce heat loss. The closed furnace took up to 1.5h to 3h to rise from room temperature to reach a steady temp (0.4Tm to 0.7Tm).
When the temperature of steady state is reached, a load was applied and the elongation of the specimen was measured using LVDT.

The extension was measured every 5s initially for the first 30 minutes. The time interval was then increased to 60s for the rest of the experimental period.

The data logger was stopped when the time reached 20h. The heating was switched off, the furnace was opened and the load was removed.

### Table1. Chemical composition of Aluminum 6061-T6 alloy

| Element     | Composition       |
|-------------|-------------------|
| Aluminum    | Balance           |
| Chromium    | 0.04% to 0.35%    |
| Copper      | 0.15% to 0.4%     |
| Iron        | 0 to 0.7%         |
| Magnesium   | 0.8% to 1.2%      |
| Manganese   | Maximum of 0.15%  |
| Other       | Maximum of 0.15%  |
| Silicon     | 0.4% to 0.8%      |
| Titanium    | Maximum of 0.15%  |
| Zinc        | Maximum of 0.25%  |

### 4. Results

Tests conducted on Aluminum 6061 T-6 alloy for varied stress (65.4 MPa and 98.1 MPa) and varied temperature (573 K, 623 K and 673 K) combinations. The results obtained from the experimentation were used to identify the material constants. The determination of the material constants within the creep constitutive equations are discussed below.
4.1 Estimation of the value of stress exponent $n$
From the gradient of ln(instantaneous strain rate) against ln(instantaneous stress) we can get the value of stress exponent $n$.

In the above graphs the value of stress exponent $n$ varies in the range $n = 1$ to 1.33 for different combinations of applied stress and applied temperature.

4.2 Estimation of material constants $\beta$ and $\alpha$:
From the gradient of ln(instantaneous strain rate) versus instantaneous stress we can get the value of material constant $\beta$. 

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Figure 3. Plots of ln(instantaneous strain rate), s$^{-1}$ against ln(instantaneous stress), MPa, for applied stress 65.4 MPa and at varying temperature 573 K (300°C), 623 K (350°C) and 673 K (400°C).

Figure 4. Plots of ln(instantaneous strain rate), s$^{-1}$ against ln(instantaneous stress), MPa, for applied stress 98.1 MPa and at varying temperature 573 K (300°C), 623 K.

Figure 5. Plots of ln(instantaneous strain rate), s$^{-1}$ against instantaneous stress, MPa, for applied stress 65.4 MPa and at varying temperature 573 K (300°C), 623 K (350°C) and 673 K (400°C).

Figure 6. Plots of ln(instantaneous strain rate), s$^{-1}$ against instantaneous stress, MPa, for applied stress 98.1 MPa and at varying temperature 573 K (300°C), 623 K (350°C) and 673 K (400°C).
From the above graphs the value of material parameter $\beta$ varies in the range $\beta = 3.2068 \times 10^{-3}$ to $6.80 \times 10^{-3}$ for different combinations of applied stress and applied temperature. The value of $\alpha$ is found to vary in the range $\alpha = 3.206 \times 10^{-3}$ to $6.80 \times 10^{-3}$ MPa$^{-1}$ for different combinations of applied stress and applied temperature.

4.3 Estimation of activation energy $Q$

The activation energy ($Q$) can be obtained by using a parameter called Larson–Miller parameter. This parameter is a useful parameter to estimate the creep activation energy of materials. The activation energy ($Q$) is found to vary in the range $Q = 165.39 \times 10^3$ J mol$^{-1}$ to $177.98 \times 10^3$ J mol$^{-1}$ for different combinations of applied stress and applied temperature.

5. Comparison of experimental creep curve and analytical creep curve:

[Figures 7-10 are shown here with captions for visual reference.]

Figure 7 Comparison of experimental and analytical creep curves, for applied stress 65.4 MPa and at temperature 573 K (300°C)

Figure 8 Comparison of experimental and analytical creep curves, for applied stress 65.4 MPa and at temperature 623 K (350°C)

Figure 9 Comparison of experimental and analytical creep curves, for applied stress 65.4 MPa and at temperature 673 K (400°C).

Figure 10 Comparison of experimental and analytical creep curves, for applied stress 98.1 MPa and at temperature 573 K (300°C).
Creep test was conducted for stress level of 65.4 MPa and 98.1 MPa at varied temperature (573 K, 623 K and 673 K) combinations. The creep curves of strain against time recorded under constant stress. The creep specimen after the fracture is shown in Fig. 2(a). The creep life of aluminum increases monotonically with decrease in applied temperature. The creep rupture behavior of aluminum for applied temperature and stress is shown in [7 to 12]. It was noticed that for creep specimen at lower temperature, shows some amount of secondary and tertiary creep which are missing at high temperature creep exposure of 673K. The creep failure time decreases with increase in temperature from 573K to 673K respectively. All of the curves exhibit a transient stage which the creep rate decreases with time. To analyze the kinetic of creep process and identify whether the steady-state creep commences, creep strain rate is plotted against time in Fig. 2(a) and strain in Fig. 2(b) on a log-log plot. Creep deformation of the pure aluminum consists of primary creep stages, and no steady-state creep stage is observed.

The various parameters of the models described above are obtained by fitting simultaneously with the experimental stress-strain data. By the experimental data it can be observed that the creep strain rate is fast in the primary creep stage, the creep strain rate reaches nearly a constant value in the secondary creep stage and at last the creep strain rate is very rapid in the tertiary creep stage. The creep rate increases with increase in magnitudes of applied stress and applied temperature. The rupture time will decrease with increase in applied stress and applied temperature, whereas the rupture stress, rupture strain and percentage elongation in length of specimen increases with increase in applied stress and applied temperature. Figure (7 to 12) shows the simulated flow curves for the are plotted together with the experimental data. The proposed model is capable of describing the overall trends in material behavior over the range of temperatures and strain rates with a reasonable accuracy. The model helps to predict the behavior with exceptional accuracy at all strain rates and temperatures due to its strong physically motivated nature.

6. Conclusion

The paper illustrates the work done with the scope of predicting Creep behavior of aluminum at high temperature. A set of unified creep constitutive equations has been developed to predict the behavior of Aluminum 6061-T6. Initially the high temperature flow behavior of Aluminum 6061-T6 alloy is studied by using isothermal creep test with the temperature ranging from 573 K to 673 K (300 to 400°C) and at applied stress levels 65.4 MPa and 98.1 MPa. By employing the experimental data, various parameters in Arrhenius model are being estimated. The analytical results are compared with
the experimental creep curve are found to be in good agreement with each other. The constitutive equations can be calibrated for other aluminum alloys. The results showed that this simple model well predicts the creep behavior of the cast aluminum parts in a broad range of temperatures, stresses and strain rates. Obviously more accurate results could be reached if those ranges could be narrowed. However, the comparison between simulations and experimental tests is both quantitative and qualitative satisfactory.

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