Investigation and optimization of Superplastic forming parameter in Aluminium alloy

M Balasubramanian\textsuperscript{1*}, C Anand Chairman\textsuperscript{2}, S Marichamy\textsuperscript{3}, V Dhinakaran\textsuperscript{4}, B Stalin\textsuperscript{5}, M Ravichandran\textsuperscript{6}

\textsuperscript{1}Department of Mechanical Engineering, University College of Engineering, Ramanathapuram Campus, Anna University, Ramanathapuram-623 513, Tamil Nadu, India.
\textsuperscript{2}Department of Mechanical Engineering, K.Ramakrishnan College of Engineering, Tiruchirappalli -621 112, Tamil Nadu, India.
\textsuperscript{3}Department of Mechanical Engineering, Sri Indu College of Engineering and Technology, Hyderabad-501 510, Telangana, India
\textsuperscript{4}Centre for Applied Research, Department of Mechanical Engineering, Chennai Institute of Technology, Kundrathur, Chennai-600 069, Tamil Nadu, India.
\textsuperscript{5}Department of Mechanical Engineering, Anna University, Regional Campus Madurai, Madurai-625 019, Tamil Nadu, India.
\textsuperscript{6}Department of Mechanical Engineering, K.Ramakrishnan College of Engineering, Tiruchirappalli -621 112, Tamil Nadu, India.

\* Corresponding author: annaunivbala76@gmail.com

Abstract. Superplasticity is the capability of materials to parade very high tensile elongation which can be more than 2500\%, appearing in eminent temperature under low stress dependent on strain rate. In this paper intentions to optimize superplastic parameters such as yield stress, ultimate stress, temperature, strain rate and strain rate sensitivity index by using hot tensile test method in AA 7075 alloy in experimental and numerical simulation method. In experimental method, the cross head velocity concept has been adopted to attain the permeability by achieving the material properties with the functions' of temperatures conditions. Finite element method using ABAQUS software was modeled to compare the experimental results.

1. Introduction
Most of the multiple complex shape components can be produced superplastically with a much lower overall manufacturing cost by reducing the number of tools, number of joints, part counts and consequently the number of forming and assembly operations. The time for forming a multi-shape components [1-5] in superplastic forming (SPF) process ranges from a few minutes to several hours due to lower strain rates in the range of $10^{-5}$ to $10^{-2}$ s\textsuperscript{-1}. In automobile and aerospace components are made of superplastic materials by adopting slow rate of below forming process technique. The learning of material characteristics at different temperature, pressure conditions with different influence factors has been made by many researchers in the last four decades. These mechanical and
physical properties are most important to understand the behavior of materials during metal forming process.

Mimaroglu & Yenihayat [6] have taken different cross head velocities for conducting uni-axial hot tensile test at constant strain rate condition. Akhtar & Liu [7] have studied the quasi-static and dynamic responses of Al 2024-T351 alloy by both analytical and experimental methods with a function of strain rate and temperature. They consider strain rates in quasi-static regime (10^4 to 10^1 s^-1) and dynamic loading (10^3 s^-1), at temperatures of 233 K, 296 K, 358 K, 422 K and 505 K. From the experimental results, they observed that the strain rate effect on the mechanical response of the material is, (a) the strength of the alloy dependent on strain rate and independent on temperature at dynamic region and (b) alloy has temperature dependent strain rate sensitivity at quasi static region.

Zhang et al. [8] have conducted two ASTM-E8 and ASTM-E2448 method of experiments to investigate the grain size and strain rate sensitivity index. The maximum elongation can reach 862 % at 800°C with the m value of 0.6. Ma et al. [9] investigated the effects of strain rate on dynamic mechanical behavior of 5A02-O Aluminum alloy at room temperature. The results of the dynamic tensile tests and compressive tests at strain rates of 1000–5000 s^-1 by split hopkinson bar as well as the results of quasi-static tests at strain rate of 0.001 s^-1. They reported that the increasing strain rate, the flow stress and tensile strength significantly increase and notable strain hardening and thermal softening behaviors are observed for 5A02-O with elongation of 63.00 % and softening ratio of 73.23 % at the strain rate of 4000 s^-1.

Kumaresan & Kalachelvan [10] have conducted multi dome forming test, under different forming pressures, temperatures and annealing times in order to determine the material parameters flow stress, strain rate and strain rate sensitivity index. They report, material after 30 min annealing acquired a higher strain rate sensitivity of 0.49 and a pole thickness of 1.33 mm in diameter of a 15 mm dome, under the forming parameters of 0.5 MPa pressure, a forming time of 60 min and temperature of 530°C. Balasubramanian et al. [11] investigated elongation, strain rate and strain rate index with a function of temperature by using hot tensile test method in a 5083 Aluminium alloy. They reported that, at the condition of 450°C temperature and 0.025 mm/sec cross head velocity, the maximum elongation of 74.42 % was achieved. Further, at same temperature and cross head velocity, 1.21 × 10^3 s^-1 and 0.39 of optimum strain rate and strain rate sensitivity index (m) value are obtained respectively. In SPF process, the important key factors such as strain rate, temperature, stress, forming duration, pressure and strain rate sensitivity index. In this paper, the optimum material parameters are predict with a function of cross head velocity and different temperature by experimental and finite element simulation method.

2. Material selection

In recent years superplastic forming material of AA 7075 alloy is mostly used in automotive and aerospace applications because of its good corrosion resistance, high strength, low cost and with fine grain structure. The 7075 aluminum alloy is subjected to continuous dynamic recrystallization in a superplastic tensile test indicate that unrecrystallized and grain structure developed by cold rolling is an important prerequisite not only for the appearance for superplasticity but also for the dynamic evolution of new grains. It is conducted that the mechanism of new grain evolution can be a deformation induced continuous reaction that is continuous dynamic recrystallization for superplastic nature. The superplastic blow forming [12] equation (1) has been written as

\[ \sigma = K\dot{\varepsilon}^m \]  

(1)

Where "σ" is the flow stress, \( \dot{\varepsilon} \) is the strain rate, "m" is the strain-rate sensitivity index of the flow stress and "K" is a material constant. The chemical composition for superplastic forming of AA 7075 alloy shown in Table 1.
Table 1. Composition of AA 7075 Alloy

|   | Si   | Fe  | Cu   | Mn  | Mg   | Cr   | Zn   | Ti   | Al   |
|---|------|-----|------|-----|------|------|------|------|------|
|   | 0.131| 0.175| 1.45 | 0.103| 2.25 | 0.182| 5.63 | 0.042| balance |

3. Experimental modeling

The test specimens from AA 7075 sheet were prepared as 1.5 mm thickness, 6 mm width and 20 mm gauge length as per guidance of ASTM E-2448 and by using wire cut EDM process [11]. The different cross head velocity of 0.01 mm/sec, 0.02 mm/sec, 0.03 mm/sec, 0.04 mm/sec and 0.05 mm/sec were consider during uni-axial hot tensile test. For each cross head velocity, the experiments were conducted with different temperature of 350°C, 380°C, 410°C, 440°C and 470°C. The optimum value of strain rate sensitivity index, strain rate and temperature was estimated [11].

\[ \varepsilon = \frac{\nu}{L} \]  (2)

The equation (2) is used to find the strain rate (\( \dot{\varepsilon} \)) with a function of cross head velocity and gauge length. The figure 1 a, b & c represent the before test specimen, after test specimen and FEA simulated profile respectively at a temperature of 410°C and cross head velocity of 0.03 mm/sec.

![Figure 1](image1.png)

(a) Before test specimen  (b) After test specimen  (c) FEA profile

4. Finite element modeling

Initial, boundary and field parameters (blow characters) are very important key factors during SPF process and also it is involved in material nonlinearity and large deformation [13]. In non-linear process, blow forming materials are taken as a rigid visco-plastic [14]. In FEA (ABAQUS software) has been simulated to carry out uni-axial hot tensile test. In preprocessing, specimen are modeled (1.5 mm thickness, 6 mm width and 20 mm gauge length), initial condition, boundary conditions, real constant and other material properties are given as a input parameters. The specimen is meshed with fine mesh [15] and apply the load on the particular line. The different cross head velocity of 0.01 mm/sec, 0.02 mm/sec, 0.03 mm/sec, 0.04 mm/sec and 0.05 mm/sec were consider during simulation based on uni-axial hot tensile test. For each cross head velocity, the simulation were carry out with different temperature of 350°C, 380°C, 410°C, 440°C and 470°C. All the simulation outputs are recorded and those results are compared with experiments results.

5. Results and discussion

Strain rate (\( \dot{\varepsilon} \)), strain rate sensitivity index (m), forming temperature (T) and flow stress (\( \sigma \)) of superplastic forming material parameters are predicting by experimentally and numerically with help of uni-axial hot tensile test approach at different temperature and different cross head velocity.
5.1. Elastic profile with different forming temperature
The percentage of elongations are evaluated at different temperatures of 350°C, 380°C, 410°C, 440°C and 470°C with different cross head velocity of 0.01 mm/sec, 0.02 mm/sec, 0.03 mm/sec, 0.04 mm/sec and 0.05 mm/sec by experimental method and FEA simulation method. The simulation results are very close to experimental values with a maximum error of 4.21%. From figure 2, it is clearly notice that, the elongation of FEA simulation profile as very close to experimental profile with a function of forming temperature and different cross head velocity. From figure 2, it is notice that, at a temperature of 410°C, the maximum elongation of 219% was obtained under cross head velocity of 0.03 mm/sec in experimentally. The percentage of elongation has been decreases with increasing temperature from 410°C. From it is observe that 410°C temperature is optimum temperature of 7075 aluminium alloy at a cross head velocity of 0.03 mm/sec.

![Elongation profile with different forming temperature](image)

**Figure 2.** Illustration of Presentation of elongation with function of temperature and cross head velocity

5.2. Yield and ultimate tensile load and stress with a function of different temperature

| Parameters                  | Temperature °C |
|-----------------------------|----------------|
| Yield load (N)              | 570            |
| Ultimate load (N)           | 700            |
| Yield stress (MPa)          | 55.88          |
| Ultimate stress (MPa)       | 66.67          |
| Maximum elongation (%)      | 135            |
|                             | 350            |
|                             | 380            |
|                             | 410            |
|                             | 440            |
|                             | 470            |

The yield load, yield stress, ultimate load, ultimate stress and elongation values at different temperature conditions are presented in Table 2. The maximum yield point and ultimate tensile point are determined with different temperature at a cross head velocity of 0.03 mm/sec. The corresponding yield stress and ultimate stress are evaluated. The maximum yield and ultimate point has been evaluated and further estimated corresponding stress values and maximum elongation at different temperature of 350°C, 380°C, 410°C, 440°C and 470°C.
is presented in table 2. From table 2, it is observed that, the both maximum yield load, stress and both ultimate tensile load and stress decreasing when increasing temperature. Further it is notice that, elongation increases when increases in temperature until optimum temperature and then decreases when increasing temperature.

5.3. Stress and strain rate with a function of temperature
The stress value and strain rate are evaluated at different temperature with different gauge height of specimen in experimentally and FEA simulation method and it is presented in figure 3. From figure 3, it is observed that, the nominal stress and strain rate obtained as a temperature of 410°C.

![Figure 3](image)

**Figure 3.** Illustration of stress with a function of strain rate at different temperature.

5.4. Strain rate sensitivity index at different temperature
The strain rate sensitivity index can be expressed [16] as equation (3)

\[
  \text{Strain rate sensitivity} = \left[ \frac{\ln \left( \frac{\sigma_1}{\sigma_2} \right)}{\ln \left( \frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2} \right)} \right] \\
  \text{(3)}
\]

Where \( \sigma_1, \sigma_2 \) - corresponding stresses on the flow curves obtained under strain rate of \( \dot{\varepsilon}_1, \dot{\varepsilon}_2 \).

| Temperature °C | \( \sigma_1 \) | \( \sigma_2 \) | \( \dot{\varepsilon} \) | \( \dot{\varepsilon}_2 \) | \( m \) |
|----------------|--------|--------|--------|--------|--------|
| 350            | 65     | 56     | 0.00833| 0.00555| 0.37   |
| 380            | 41     | 36     | 0.0081 | 0.0058 | 0.39   |
| 410            | 26     | 25     | 0.0051 | 0.0047 | 0.48   |
| 440            | 22     | 20     | 0.0026 | 0.0002 | 0.36   |
| 470            | 19     | 17     | 0.005  | 0.0036 | 0.34   |

Table 3. Strain Rate Sensitivity Index Values at Different Temperature Conditions

In superplastic forming material, the most key factor is strain rate sensitivity index of \( m \) value because of it is resistance to necking during tensile-tests. Further, highest \( m \)-value leads to the better superplasticity of an alloy. The strain rate sensitivity index value is dependent on temperature and strain-rate. The maximum index (\( m \)) value has a corresponding strain-rate and temperature regions which are the optimal for superplastic forming. From Table 3, it is observed that, the maximum strain rate sensitivity index obtained as 0.48 at a temperature of 410°C and a cross head velocity of 0.03 mm/sec. The maximum strain rate sensitivity index value gives better slow flow rate for filling the die cavity without wrinkle effect.
6. Conclusions
In this article, experiments and FEA simulations has been carried out for investigating the SPF parameters in AA 7075 alloy.
- The temperature ranges of 350°C and 470°C, the very good formability has obtained in AA 7075 alloy, from which optimum temperature of 410°C obtained.
- The maximum percentage elongation of 219 % was obtained.
- A maximum strain rate sensitivity index of 0.48 achieved at a optimum temperature of 410°C and a cross head velocity of 0.03 mm/sec.

7. References
[1] Pradeep P, Ayyanar S, Balasubramanian M, Ramanathan K and Senthilkumar V S J. App. Sci. 12 1048.
[2] Balasubramanian M, Ramanathan K and Senthilkumar V S 2012 Int. J. Adv. Mat. Resear. 487 116.
[3] Balasubramanian M, Ramanathan K and Senthilkumar V S 2013 Proce. Engg. 64 1209.
[4] Balasubramanian M and Ramanathan K 2015 Int. J. App. Engg. Resear. 10 3746.
[5] Balasubramanian M, Ganesh P, Ramanathan K and Senthilkumar V S 2017 J. Mech. Engg. 63 255.
[6] Mimaroglu A and Yenihayat O F 2003 J. Mater. De. 24 189.
[7] Akhtar K S and Liu H 2012 Int. J. Plasti. 36 1.
[8] Zhang T, Yong Liu, Daniel G, Sanders, Bin Liu, Zhang W and Zhou C 2014 J. Mat. Sci. Engg.-A 608 265.
[9] Ma H, Huang L, Tian Yi and Li J 2014 J. Mat. Sci. Engg.-A 606 233.
[10] Kumaresan G and Kalaichelvan K 2014 J. Allo. Comp. 583 226.
[11] Balasubramanian M, Stalin B, Ramanathan K and Ravichandran M 2020 Mater. Today.: Proc. 21 324.
[12] Balasubramanian M and Ramanathan K 2015 Int. J. App. Engg. Res. 10 429.
[13] Khamei A A and Dehghani K 2015 J. Mat. Sci. Engg.-A. 627 1.
[14] Balasubramanian M, Ganesh P, Ramanathan K and Senthil Kumar V S 2015 J. Mech. Engg. 61 365.
[15] Balasubramanian M, Sathish Kumar M K, Stalin B and Ravichandran M 2020 Mater. Today: Proc. 24 1424.
[16] Senthil Kumar V S, Viswanathan D and Natarajan S 2006 J. Mat. Proc. Tech. 173 247.