Superplastic behaviour of AA5083 sheets in the presence of an oscillating load

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Abstract. The superplastic flow behaviour of AA5083 sheets was investigated at 450°C in the presence of a minor oscillating load. Uniaxial tensile specimens were tested to fracture at constant strain rates with a minor oscillating load superimposed onto the monotonically increasing tensile load. In each test, the oscillating load was applied as a sine wave having a constant amplitude of 0.5 N and a constant frequency. A series of tests was conducted in which the strain rate ranged from 0.001 to 0.4 s⁻¹ and the frequency of the oscillating load ranged from 10 to 40 Hz. And other tensile specimens were subject to a constant mean load with a superimposed oscillating load until a predetermined elongation was reached. The flow behaviour of AA5083 showed a significant sensitivity to the oscillations although the tensile strengths remained practically unchanged. The addition of a minor oscillating load resulted in a 20% - 50% relative increase in fracture strain for the strain rates considered compared to the same tensile tests without oscillation. Finite element simulation of the tensile tests conducted at constant mean load with superimposed oscillations were carried out with LS-Dyna using material data obtained from the experiments. The numerical simulation results were compared with experimental results obtained under the same loading conditions to confirm their validity. The addition of a minor oscillating load led to greater uniformity in thickness in the specimen gauge. It can be concluded that superimposing a minor oscillating load during superplastic forming results in significantly greater deformation prior to fracture.

1. Introduction

Aluminum AA5083 is a non-heat-treatable aluminum alloy with excellent cold formability and can reach moderate levels of superplasticity [1]. This alloy is affordable and has reasonable corrosion resistance and good mechanical properties, which make it ideal for aerospace, marine, and automotive applications [2].

1.1. Introduction to Superplastic Forming

A material is said to display superplastic behavior when it exhibits significant plastic deformation (an elongation >200%) at elevated temperature without necking prior to fracture [3]. Both the mechanical properties (elongation, UTS, optimum forming temperatures, strain rate dependence, etc.) and the microstructural characteristics of superplastic aluminum alloys have been investigated [4–9]. Of particular interest, published research has shown the effectiveness and results of superplastically
deforming AA5083 sheets [10, 11]. The severe deformations occurring in superplastic forming are primarily achieved through Grain Boundary Sliding (GBS). Furthermore, the high levels of grain boundary sliding are accompanied by an additional accommodating deformation mechanism, and traditional GBS models are separated into two categories: diffusional accommodated and dislocation accommodated GBS. Despite the very large deformations that can be achieved, the main drawback to the widespread use of superplastic forming is the significant time that is required to form an industrial part, spanning from two to ten minutes. This limits the numbers of parts that can be formed [12].

Blow forming processes can take advantage of superplastic materials to plastically deform sheets without necking. This has allowed the automobile industry to superplastically form complex parts having a relatively uniform thickness distribution. In this process, a metallic blank may be pre-heated and then placed in a die that is heated to the prescribed forming temperature. A pressure vs. time curve is used to control the pressure of air or argon gas, as the blank is gradually formed against the surface of the die. This process has been successfully used to reduce the weight of parts used in the automotive and aerospace industries.

1.2. Improvement of Superplastic Capabilities and Processes
Industrial forming times could be reduced if superplasticity could be carried out at increased strain rates compared to the conventionally slow superplastic forming strain rates. Much effort has been made to achieve increased superplastic forming times described as High Strain Rate (HSR) superplasticity. HSR research is largely focused on the refinement of the grains in the microstructure due to the relationship between decreasing grain size and increasing maximum elongation. HSR studies include the investigation of severe plastic deformation processes as a pre-treatment to refine grains and theoretically exhibit superplasticity at higher than conventional strain rates.

The effectiveness of an oscillating load on material behavior has been shown in ultrasonic welding [13, 14]. Ultrasonic welding uses high-frequency vibrations to weld two clamped components, and the result is a high strength and highly repeatable weld. Moreover, superimposing ultrasonic oscillations in tensile tests to improve deformation has also been investigated [15, 16, 17, 18]. Superimposed oscillations hypothetically improve deformation effectiveness due to the oscillatory stress generating a mean stress lower than that of the stress strain curve for a static tensile loading.

1.3. Constitutive Modelling of Superplastic Forming Processes
Due to the use of variable pressure vs. time curves, it is of great value to develop constitutive models of the flow stress that can be used to simulate the superplastic forming process. Thus, the objective of this paper is to carry out experimental testing and obtain data that can be used to develop a constitutive model of the superplastic deformation with, and without, oscillations. Additionally, finite element (FE) simulations are very useful to optimize the superplastic forming of specific parts.

Superplastic deformation is regarded as a creep process lying within region II of the sigmodal stress vs strain rate curve [19]. This region is often defined by a strain rate sensitivity index ($m=\Delta(\log(\sigma))/\Delta(\log(\epsilon)))$) surpassing 0.4. Additionally, the activation energy in Region II is close to that required for grain boundary diffusion to take place. As a result, maximum ductility occurs within Region II, so it is often characterized as the Superplastic region. The importance of the strain rate sensitivity index is further seen with its utilization in all the most cited visco-plastic constitutive equations. These constitutive models include the power law, sinh law, the Bird-Mukherjee-Dorn equation, and the unified constitutive model [20]. Despite previous models utilizing a constant $m$-value, recent studies have indicated that this practice is inaccurate and can negatively skew the predictions. Additionally, despite the power law being frequently utilized in FE simulations due to its simplicity it has limitations due to its inability to predict the softening and damage behaviors during superplastic forming.

This present study aims to improve the current framework of superplastic forming by incorporating the material response in the presence of a superimposed oscillating load.
2. Experimental procedures

2.1. Specimen preparation
Specimens were made from a 1.4-mm thick AA5083 sheets, whose chemical composition is shown in Table 1. Sub-size specimens were cut to a specified geometry adopted from the literature [10], which consisted of an 18-mm gauge length and an 8-mm gauge width, as recommended in previous studies [21]. Specimens were prepared using wire EDM such that the major stress axis was always parallel to the rolling direction of the sheet. This sub-sized specimen geometry is advantageous because it ensures that the specimen will fracture before the gauge length stretches outside the limits of the available furnace. This specimen geometry also facilitated the comparison of results with data published by other researchers.

| Alloy   | Fe  | Mg  | Mn  | Cu  | Si  | Cr  | Ti  | Zn  | Others |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|--------|
| AA5083  | 0.20| 4.75| 0.8 | 0.04| 0.15| 0.15| 0.05| 0.05| < 0.15 |

2.2. Testing equipment
The custom-built equipment used to carry out the experiments includes a well-insulated furnace with a double-layer quartz window, a pneumatic opening mechanism, titanium rods and fixture for holding the specimen, an electromagnetic mechanical waveform generator, an electric waveform generator, a National Instruments data acquisition and control device, a secondary load cell, and tests were conducted on an MTS tensile testing machine. Figure 1 shows a schematic of the test setup.

The furnace contains electric heaters that surround its two semi-circular chambers for uniform temperature distribution in accordance with the ASTM E2448-18 standard for determining superplastic properties of aluminum. The pneumatic lifter is used to raise and lower the furnace when mounting the specimen. Two steel rods enter through the openings in the top and bottom of the furnace to hold the specimen as well as transfer the load from the MTS testing machine. The openings in the furnace are sealed with silica cotton when it is operating. One of the rods is attached to a pair of electromagnets that induce oscillations in the loading direction. Sine wave signals are generated by a waveform generator, and the electromagnets convert the signals into an oscillating load which is mechanically transferred to the specimen through the steel rods. The applied oscillating load was calibrated for each strain rate and frequency using the MTS load cell. Figure 2 shows a recorded load oscillation wave at 0.5 N amplitude of 10 Hz frequency with compensated pre-loading.

![Figure 1. Schematic of the experimental setup.](image-url)
2.3. Testing procedures

The tensile tests were conducted in accordance with the ASTM E2448-18 standard except for the specimen geometry. For each condition, 3 repeat tests were performed. Before testing, the gauge length and width of each specimen was measured using Mitutoyo calipers for accuracy. Once the oscillating load was calibrated, the furnace was closed and preheated to 450°C. And once the temperature reached 450°C, the furnace was raised up and the specimen was mounted into the gripping fixtures. The top and bottom of the specimen were placed in contact with the temperature probes that are fastened in place with steel wire. The furnace was then lowered and sealed. The start time and temperature were recorded. Once the furnace temperature stabilized at 450°C, the specimen was left to soak for five minutes, in accordance with industrial practice. During this process the crosshead position was adjusted to minimize built-up stress due to thermal expansion. Then the oscillating load was activated, and the tensile test was started. After the test was completed, the specimen was removed, and the chamber was left to preheat for the next test. An MTS Advantage Video Extensometer (AVX) was used to record displacement data in the gauge length. These data were used to confirm the elastic modulus of AA5083 at 450°C, and by comparing the data recorded by the AVX and the crosshead data, a relation between crosshead displacement and gauge length displacement was established. This equation was used to process load-displacement data and calculate the true stress-effective plastic strain for each test.

3. Results

Two types of tensile tests were performed: the first type consisted of conventional tensile testing where a monotonically increasing load was applied at a constant engineering strain rate ranging from 0.001 to 0.4 s⁻¹ that leads to a flow curve obtained with and without a superimposed oscillation. The second type consisted of applying a constant load to the specimen and letting the specimen deform until it reached a certain predetermined strain. In this type of test, the time required to reach the target strain was recorded and the minimum thickness in the gauge length was measured after the test. This type of loading leads to a range of strain rates during a single test which provides an opportunity to validate the material model as it is defined by constant strain rate flow curves.

3.1. Conventional tensile testing

To be able to compare results obtained with and without a superimposed oscillating load, a series of benchmark tests were first performed without oscillations. Then the same test conditions were repeated with superimposed oscillation loads. Figure 3 shows the tensile strength versus strain rate, with and without oscillation.
It was observed that for both the benchmark tests and those with oscillations, the variability in the measurement of the tensile stress remained less than 1%, which makes it impractical to show any error bars on the graph. In addition, the variability observed for different frequencies (10, 20 and 40Hz) also remained less than 1%. Figure 3 shows the mean values of each series of tests.

Figure 4 compares the recorded value of the total percent elongation (TPE), with and without oscillations. The variability for these measurements was found to be 7%, which was greater than that of the tensile stress. In Figure 4 the presented value is the mean of each series of tests.

Figure 3. Maximum true tensile stress of AA5083 versus strain rate at 450°C with and without oscillations.

Figure 4. Total percent engineering elongation of AA5083 at 450°C, without and with superimposed oscillations at 0.5N amplitude and 10Hz frequency.
3.2. Constant-load tensile testing
In this second series of tests, specimens were subject to a constant load ranging from 147.1 to 269.7 N, either with or without a superimposed oscillating load. Since the flow behavior in the first series of tests did not show any sensitivity to the frequency of the oscillations, this second series of tests was carried out at a single frequency of 10 Hz. Figure 5 presents the minimum measured thickness across the gauge length for different levels of applied tensile force, both with and without oscillation. The maximum variability for the repeat tests was 1.7% and the data points presented in Figure 5 are the averages.

![Figure 5](image-url)

**Figure 5.** Minimum thickness measured across the gauge length of AA5083 specimens subject to a constant load at 450°C until a strain of 171% was reached.

4. Discussion
According to Figure 3, AA5083 sheet specimens show a positive strain rate sensitivity: indeed, the tensile stress at a strain rate of 0.001 s\(^{-1}\) is below 20 MPa, whereas it increases fourfold to reach 80 MPa at a strain rate of 0.4 s\(^{-1}\). And the same trend is observed whether a minor oscillating load is applied or not. Therefore, superimposing an oscillating load during tensile testing did not make any measurable difference on the tensile stress for the entire range of strain rates covered by this study.

In contrast, Figure 4 shows that the total percent elongation decreases with increasing strain rates. At a strain rate of 0.001 s\(^{-1}\) the specimen can deform over 200%, but when the strain rate reaches 0.4 s\(^{-1}\) the total elongation decreases to about 140%. The effect of a superimposed minor oscillating load on the mechanical behavior of AA5083 can be described by comparing the percent improvement at different strain rate. This information is plotted in Figure 6. The difference in tensile stress at various strain rates is less than 5 percent, however, the improvement in total elongation due to the oscillations varies from 20 to 50%.

The promising results of superimposing an oscillating load on the flow behavior of AA5083 sheets suggests that the production rate of superplastically formed parts can be significantly improved.
5. Constitutive model

One of the most accurate constitutive models to describe the behavior of AA5083 was developed by Majidi-Jahazi-Bombardier and is known as the VmV model [20]. This model can be calibrated to make accurate predictions at lower strain rates. However, the accuracy of the model decreases at higher strain rates. The absolute values of the residuals predicted by the VmV model compared to AA5083 experimental data remain below 5 MPa for strain rates up to 10^{-2} s^{-1}. However, these values rise to about 20 MPa for a strain rate of 10^{-1} s^{-1}. This experimental study considered the effect of oscillations for strain rates up to 0.4 s^{-1} and, for numerical predictions to be accurate up to this strain rate, a constitutive model should exhibit an acceptable accuracy for this full range of strain rates.

5.1. Proposed constitutive model

As it has been pointed out, the behavior of AA5083 at 450°C is sensitive to strain rate. The trend of this strain rate sensitivity can be determined by observing the changes that occur as a function of the controlling variable. In Figure 3, the fitted line is a power law function with R-squared value of 0.992. This confirms that the strain rate sensitivity can be described by a power law function. On the other hand, the true stress-effective plastic strain curves of AA5083, both with and without oscillation, show a strain softening trend. This trend cannot be described by a power law function. However, strain softening behavior can be adequately described by a second-degree polynomial function. Equation (1) is the proposed function that describes the material behavior in terms of both strain and strain rate. Equation (2) is a second-degree polynomial function that is suggested to describe the flow behavior. And Equation (3) is the suggested function to describe strain rate sensitivity of the stress, where \(d\) and \(e\) are simply scalar material parameters. By implementing Equations (2) and (3) into Equation (1) and considering the \(g(\dot{\varepsilon})\) as a linear function with slope of 1, Equation (4) will be readily obtained.

\[
\sigma = f(\varepsilon) \ast g(\dot{\varepsilon}) + h(\dot{\varepsilon}) \quad (1)
\]

\[
f(\varepsilon) = (a\varepsilon^2 + b\varepsilon + c) \quad (2)
\]

\[
h(\dot{\varepsilon}) = d\dot{\varepsilon}^e \quad (3)
\]

\[
\sigma = (a\varepsilon^2 + b\varepsilon + c) \ast \dot{\varepsilon} + d\dot{\varepsilon}^e \quad (4)
\]

where \(\varepsilon\) is the plastic strain, \(\dot{\varepsilon}\) is the strain rate, \(a, b, c,\) and \(d\) are material constants and \(e\) is the strain rate coefficient.

Figure 6. Effect of superimposing an oscillating load on the tensile stress and total elongation of AA5083 at 450°C.
5.2. Quality of prediction

Using the MATLAB curve fitting tool, the material parameters in the proposed model were optimized and fitted to the experimental data for AA5083 tested at 450°C and are shown in Table 2.

Table 2. Material parameters in the proposed material model for AA5083 at 450°C.

|                  | a     | b    | c    | d    | e    |
|------------------|-------|------|------|------|------|
| No oscillation   | -261.5| 85.61| 18.27| 88.86| 0.2758|
| With Oscillation | -210.3| 88.98| 12.87| 84.11| 0.2446|

Figure 7 compares the residuals of the predictions for the corresponding flow stress compared to the experimental data. The accuracy of the predictions remains acceptable for the entire range of strain rates considered. At the lower end of strain rates, the absolute value of residuals does not exceed 5 MPa. At the higher end of strain rates this value remains below 7 MPa.

![Figure 7](image)

**Figure 7.** Differences between predicted and experimental data (a) without oscillations and (b) with oscillations.

5.3. Simulations

The above-mentioned material model was implemented as a user-defined material model in LS-Dyna. The tensile specimen was modelled with Belytschko-Tsay shell elements having 5 integration points through the thickness. This series of simulations covered the conditions shown in Figure 4. The deformation was applied by allowing contact between the tensile specimen and the solid elements of the test fixture rather than applying constraints as boundary conditions. This strategy considers the flow of material throughout the specimen, from the gripping area through to the gauge area that is observed in experiments. LS-Dyna requires as input the true stress versus effective plastic strain in uniaxial tension. In this case, since the experimental flow curves were not obtained in uniaxial tension due to the specimen geometry, a series of iterative simulations was performed to scale the input flow curve until the experimental force displacement data were accurately predicted. In the second series of simulations the constant load conditions that are described in Figure 5 were predicted. A constant load was applied to the top fixture while keeping the bottom fixture stationary. The simulation was set to terminate upon reaching the 171% strain, and the minimum thickness predicted in the gauge was exported and compared.
to the experimental data. This comparison is presented in Figure 8 showing a good degree of accuracy under all loading conditions.

![Figure 8](image.png)

**Figure 8.** Comparison of minimum thickness in the specimen gauge measured from experiments (Exp) and predicted by simulations (Sim) both with oscillations (W/O) and without oscillations (N/O).

6. Conclusion

Superimposing a minor oscillating load having a sine wave pattern, an amplitude of 0.5 N and a frequency ranging from 10–40 Hz has been shown to have a significant effect on the flow behavior of AA5083 during superplastic forming at 450°C. Although the tensile stress is not sensitive to superimposed oscillations, the total elongation is very sensitive to the oscillating load. Indeed, the relative improvement in total elongation varies from 20 to 50% depending on the applied strain rate. This allows the sheet material to achieve significantly higher levels of plastic deformation before the onset of fracture. Minimum thickness measurements in the gauge of deformed test specimens also confirmed that the presence of oscillating loads during forming result in greater value of the minimum thickness which indicates a slower rate of thinning in the specimen. These results suggest that the addition of a minor oscillating load will allow industrial parts to be safely formed superplastically at great strain rates, and therefore at higher rates of production. Finally, a simple empirical material model has been proposed that is able to accurately describe the superplastic behavior of AA5083 at 450°C with and without the presence of minor oscillations.

References

[1] Giuliano G 2011 Superplastic forming of advanced metallic materials *Superplastic forming of advanced metallic materials* (Woodhead Publishing Limited) p 15
[2] Davoodi B, Payganeh G H and Eslami M R 2012 Cutting forces in dry machining of aluminum alloy 5083 with carbide tools *Advanced Materials Research* vol 445 pp 259–62
[3] Zhang K F and Jiang S S 2014 Superplastic Forming *Comprehensive Materials Processing* vol 5 (Elsevier) pp 371–92
[4] Zelin M G 1997 On micro-superplasticity *Acta Mater.* 45 3533–42
[5] Mikhaylovskaya A V., Yakovtseva O A, Sitkina M N, Kotov A D, Irzhak A V., Krymskiy S V. and Portnoy V K 2018 Comparison between superplastic deformation mechanisms at primary and steady stages of the fine grain AA7475 aluminium alloy Mater. Sci. Eng. A, Struct. Mater. Prop. Microstruct. Process. 718 277–86

[6] Yakovtseva O A, Sitkina M N, Kotov A D, Rofman O V. and Mikhailovskaya A V. 2020 Experimental study of the superplastic deformation mechanisms of high-strength aluminum-based alloy Mater. Sci. Eng. A 788 139639

[7] Wang X, Li Q, Wu R, Zhang X and Ma L 2018 A Review on Superplastic Formations Behavior of Al Alloys ed G P Dinda Adv. Mater. Sci. Eng. 2018 7606140

[8] Liu X, Ye L, Tang J, Dong Y and Ke B 2021 Superplastic deformation mechanism of an Al-Mg-Li alloy by high resolution surface studies Mater. Lett. 301 130251

[9] Masuda H and Sato E 2020 Diffusional and dislocation accommodation mechanisms in superplastic materials Acta Mater. 197 235–52

[10] Hossempour S J 2009 An investigation into hot deformation of aluminum alloy 5083 Mater. Des. 30 319–22

[11] Das S, Riahi A R, Meng-Burany X, Morales A T and Alpas A T 2012 High temperature deformation and fracture of tribo-layers on the surface of AA5083 sheet aluminum–magnesium alloy Mater. Sci. Eng. A 531 76–83

[12] Kridli G T, Friedman P A and Boileau J M 2021 Manufacturing processes for light alloys Mater. Des. Manuf. Light. Veh. 267–320

[13] Singh V and Agrawal P 2008 Analysis of Bonding Strength of Ultrasonic Welding Process vol 9001

[14] Drozdov A D and Shtemler Y 1996 Evaluation of bond strength at ultrasonic welding

[15] Winsper C E and Sansome D H 1968 A review of the application of oscillatory energy to metals deforming plastically Adv. Mach. Tool Des. Res. 1967 1349–60

[16] Ye C 2016 The effect of ultrasonic waves on tensile behavior of metal The effect of ultrasonic waves on tensile behavior of metal (Windsor: University of Windsor)

[17] Daud Y, Lucas M and Huang Z 2007 Modelling the effects of superimposed ultrasonic vibrations on tension and compression tests of aluminium J. Mater. Process. Technol. 186 179–90

[18] Kirchner H O K, Kromp W K, Prinz F B and Trimmel P 1985 Plastic deformation under simultaneous cyclic and unidirectional loading at low and ultrasonic frequencies Mater. Sci. Eng. 68 197–206

[19] Mohamed F A 2011 Micrograin superplasticity: Characteristics and utilization Materials (Basel). 4 1194–223

[20] Majidi O, Jahazi M and Bombardier N 2018 A viscoplastic model based on a variable strain rate sensitivity index for superplastic sheet metals Int. J. Mater. Form. 2018 124 693–702

[21] Dastgiri M S, Kiawi L, Sarraf I S, Ryzer E and Green D E 2021 Influence of Specimen Preparation Methods on the Mechanical Properties and Superplastic Behavior of AA5083 Sheets Miner. Met. Mater. Ser. 1573–83