Analytical and Experimental Investigation for Tensile and Compressive Creep of the A3003P Aluminium Alloy Used for Plate-Fin Heat Exchanger*

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Analytical and experimental analysis for tensile and compressive creep properties of fine and coarse-grained aluminium alloy, A3003P, used for plate-fin heat exchanger are presented for temperatures from 400°C to 600°C and stresses between 0.255 MPa and 6.370 MPa. Investigation for parameters' effect on the behaviour of the time-dependent flow of material was carried out. For analytical investigation, the grain-size mechanism was applied to both tension and compression creep tests. Creep-strain rate increases with increasing both temperature and stress, while decreasing with coarse grain size. For loading mode, experimental results showed lower creep strain in compression than in tension for all stresses investigated. Nevertheless, numerical analysis showed identical behaviour for both tension and compression. Good agreement was found between the experimentally determined creep strain and analytical predictions at lower stress level. However, at higher stresses considerable deviations from the experimental results were recorded for the analytical findings. Though the grain-size mechanism is applicable in case of tension for pure aluminium, modification becomes necessary when compression is applied.

Key Words: Heat Exchanger, Plate Fin, Aluminium, Grain Size, Deformation Mechanism Map, Tensile Creep, Compressive Creep, FE-Analysis, Experiment, Parametric Study

1. Introduction

Plate-fin heat exchanger is widely used in industrial applications like chemical plants, gas turbine, automotive industries, ... etc. Using the aluminium alloys as a material for the plate fin is also widely spread for its lesser weight and lower cost. Stacking-for-bonding process is one of the main jobs that the plate fin should go through. Plate fins are stacked under pressure of about 0.15 to 0.30 MPa and then be

put after time in a furnace for bonding by brazing under about 500 to 600°C. During this production step, the fin is subjected to compression under high temperature for a considerable long time, which may lead to compressive creep problem.

Tensile creep problems of aluminium were widely investigated⁽¹⁾⁻⁽⁶⁾; compressive creep cases were rarely discussed in the literatures⁽⁷⁾⁻⁽⁸⁾.

Deformation mechanisms, that characterise the plasticity and creep of metals, have received a considerable interest and in accordance, various types of deformation mechanism maps have been proposed^{(9),(10)}. The mechanism maps that will be taken into consideration here are mainly two. The first is the Ashby model⁽⁹⁾ in which the stress, or normalised stress, is plotted against either the temperature or the homologous temperature, respectively. This type of map must be drawn for one specific grain size. The second is Mohamed-Langdon (hereinafter referred to as grain-size) mechanism⁽¹⁰⁾ in which

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Fig. 1 Comparison between Grain-size mechanism and Ashby mechanism using different activation energy (Q) values

various deformation processes are described at different grain sizes.

The two mechanisms; Ashby mechanism and grain-size mechanism have been compared in the light of the experimental results presented for pure aluminium by Guard and Hibbard⁽¹⁾. This comparison is shown in Fig. 1. In the analysis by ABAQUS⁽¹¹⁾, different values for the activation energy $Q^{(1),(12),(13)}$ have been adopted in the grain-size mechanism. By comparing the analytical results with the experimental data, good agreement can be noticed between the grain-size mechanism's results-for specific Q values-and the experimental data.

Grain-size mechanism was therefore, applied to the cases of this investigation. The effects of various parameters on the creep strain were examined analytically and experimentally. Main parameters that analytically investigated were grain size, temperature, stress level and loading mode. Experiments included the investigation for stress and temperature levels and loading mode effects on creep strain of the aluminium alloy A3003P used for plate-fin heat exchanger.

Comparative analysis was then held between the analytical and experimental results. Validity of the deformation mechanism map used in the analysis was also examined.

2. Analysis

2.1 Specimen geometry and FE-Model

Figure 2 illustrates different parts of the plate-fin heat exchanger taken into consideration. Two-dimensional finite element analysis was carried out for the straight part of the corrugated fin shown in Fig. 2. The fin was modelled with 4-node axisymmetric solid elements and mesh was generated using the FE program ABAQUS⁽¹¹⁾ as illustrated in Fig. 3. For simplicity, the curved part of the fin has not been included in the analysis.

Fig. 2 Schematic representation for the components of the plate-fin heat exchanger

Fig. 3 Specimen design and mesh generation with boundary conditions applied in the FE analysis

2.2 Variables of the study (parametric study)

In this investigation, the effects of various parameters on the creep strain are discussed. The parameters of the study are grain size, temperature, applied stress and loading mode. Stresses were varied from 0.255 to 6.370 MPa. Grain size were changed from 1 to 200 μm for stress of 0.255 MPa and from 1 to 50

μm for stress of 0.637 MPa and from 0.1 to $1\mu\text{m}$ for stress of 6.370 MPa. This is because of the nature of the grain-size mechanism in which the deformation mode changes as load changes up to certain limit at which the deformation mode does not give any variation in spite of any increase in the grain size. Temperature ranged from 400 to 600°C . Loading mode applied was both tension and compression.

2.3 Deformation mechanism

As stated above in the Introduction, the grain-size mechanism is applied to the cases of this study. In this model the governing equations can be briefly stated as follows:

$$\text{Climb}^{(14)} \quad \dot{\epsilon} = 2.5 \times 10^6 \frac{D_i G b}{kT} \left(\frac{\sigma}{G} \right)^{4.4} \quad (1)$$

$$\text{Nabarro-Herring}^{(15),(16)} \quad \dot{\epsilon} = 28 \frac{D_i G b}{kT} \left(\frac{b}{d} \right)^2 \left(\frac{\sigma}{G} \right) \quad (2)$$

$$\text{Coble}^{(17)} \quad \dot{\epsilon} = 66.8 \frac{D_{gb} G b}{kT} \left(\frac{b}{d} \right)^3 \left(\frac{\sigma}{G} \right) \quad (3)$$

Where, $\dot{\epsilon}$ is the steady-state creep rate, D_i is the coefficient for lattice self-diffusion (calculated by Eq. (4)), G is the shear modulus (determined through Eq. (5)), b is the Burgers vector ($2.86 \times 10^{-8} \text{cm}$ in Al), k is the Boltzmann's constant ($1.38 \times 10^{-23} \text{J/K}$), T is the absolute temperature, d is the grain size, and D_{gb} is the coefficient for grain boundary diffusion and determined by Eq. (6).

$$D_i = 1.86 \exp(Q/RT) \text{ cm}^2 \text{ s}^{-1} \quad (4)$$

$$G = G_o - G_T T \quad (5)$$

$$D_{gb} = 1.86 \exp(0.6Q/RT) \text{ cm}^2 \text{ s}^{-1} \quad (6)$$

Here, Q is the activation energy, R is the gas constant ($8.314 \text{ J/(mol} \cdot \text{K)}$), G_o is the value of G obtained by a linear extrapolation to absolute zero ($G_o = 3.002 \times 10^4 \text{ MPa}$) and G_T is the variation of G per degree Kelvin.

Activation energy, Q , applied in Eqs. (1)–(3) (through the calculations of D_i and D_{gb} in Eqs. (4)–(6)) was investigated through various values proposed in the literatures^{(9),(12),(13)}. Comparison of those values is included in Fig. 1. Values for Q adopted in deformation (grain-size) mechanism⁽⁹⁾ and that used by Lundy and Murdock⁽¹²⁾ reveal the nearest values to the experimental results. Therefore, value of $Q = 34\,230 \text{ cal/mol}$ was used in Eqs. (1)–(3). G_o that used for calculation of G was determined by extrapolation.

By adopting the method described by Mohamed and Langdon⁽⁹⁾ for constructing the deformation map based on grain size (grain-size mechanism), the deformation mechanism map for the current case was obtained as shown for example in Fig. 4. In this figure, the map is drawn for temperature of 400°C .

To determine the deformation mechanism at

Fig. 4 How to determine the deformation mode at specific applied stress and certain grain size using the grain-size mechanism

certain applied stress and specific material grain size, a vertical line corresponding to the applied stress is drawn (in Fig. 4 it is 0.255 MPa). This line will intersect the horizontal line which represents the material grain size (here in Fig. 4 consider the line of $50\mu\text{m}$). Point of intersection (circled in Fig. 4) falls in the region of the deformation mechanism that is expected to prevail under this condition (Nabarro-Herring in this case).

After determining the deformation mechanism for each condition of the analysis, the constitutive equations shown above (Eqs. (1)–(3)) are used to calculate the strain rate for each deformation mechanism. The deformation mechanisms and creep-rate constitutive equations at various grain sizes, temperature and stress levels are demonstrated in detail through Table 1.

Three-dimensional representation for the deformation mechanism map is shown in Fig. 5. This map was drawn by calculating the deformation map at various homologous temperatures (T/T_M , where T_M is the melting point of the material and equal to 933°K) ranging from 0.1 to 0.9. This graph shows the deformation mechanisms expected at all temperature ranges possible for application.

3. Analytical Results

The tensile creep strain at time 26–28 hr is plotted as a function of applied stress for fine and coarse-grained A3003P Al-alloy in Fig. 6(a) and at time 196 hr in Fig. 6(b). Tensile creep strain increases as stress increases. Above-the-normal creep strain, values were recorded at high stress level; 6.370 MPa

Table 1 Variables of the analysis and the resulted deformation mechanism

Analytical Test Conditions			Deformation Mechanism at Applied Stress	
Temperature (°C)	Grain Size (μm)	Governing Equation	0.255 (MPa)	0.637 (MPa)
400	1	$\dot{\epsilon} = 1.87 \times 10^{-2} \sigma$	Coble	Coble
	2	$\dot{\epsilon} = 2.34 \times 10^{-3} \sigma$	↓	↓
	5	$\dot{\epsilon} = 1.50 \times 10^{-4} \sigma$	↓	↓
	10	$\dot{\epsilon} = 1.87 \times 10^{-5} \sigma$	↓	↓
	20	$\dot{\epsilon} = 2.44 \times 10^{-6} \sigma$	N-H	N-H
	50	$\dot{\epsilon} = 3.91 \times 10^{-7} \sigma$	↓	Climb
	100	$\dot{\epsilon} = 9.77 \times 10^{-8} \sigma$	↓	↓
450	200	$\dot{\epsilon} = 6.54 \times 10^{-3} \sigma^{4.4}$	Climb	↓
	1	$\dot{\epsilon} = 5.03 \times 10^{-2} \sigma$	Coble	Coble
	2	$\dot{\epsilon} = 6.29 \times 10^{-3} \sigma$	↓	↓
	5	$\dot{\epsilon} = 4.03 \times 10^{-4} \sigma$	↓	↓
	10	$\dot{\epsilon} = 5.34 \times 10^{-5} \sigma$	N-H	N-H
	20	$\dot{\epsilon} = 1.34 \times 10^{-5} \sigma$	↓	↓
	50	$\dot{\epsilon} = 2.14 \times 10^{-6} \sigma$	↓	Climb
500	100	$\dot{\epsilon} = 5.34 \times 10^{-7} \sigma$	↓	↓
	200	$\dot{\epsilon} = 4.13 \times 10^{-2} \sigma^{4.4}$	Climb	↓
	1	$\dot{\epsilon} = 1.19 \times 10^{-1} \sigma$	Coble	Coble
	2	$\dot{\epsilon} = 1.48 \times 10^{-2} \sigma$	↓	↓
	5	$\dot{\epsilon} = 9.49 \times 10^{-4} \sigma$	↓	↓
	10	$\dot{\epsilon} = 2.33 \times 10^{-4} \sigma$	N-H	N-H
	20	$\dot{\epsilon} = 5.83 \times 10^{-5} \sigma$	↓	↓
550	50	$\dot{\epsilon} = 9.33 \times 10^{-6} \sigma$	↓	Climb
	100	$\dot{\epsilon} = 2.33 \times 10^{-6} \sigma$	↓	↓
	200	$\dot{\epsilon} = 2.09 \times 10^{-1} \sigma^{4.4}$	Climb	↓
	1	$\dot{\epsilon} = 2.51 \times 10^{-1} \sigma$	Coble	Coble
	2	$\dot{\epsilon} = 3.14 \times 10^{-2} \sigma$	↓	↓
	5	$\dot{\epsilon} = 3.40 \times 10^{-3} \sigma$	N-H	N-H
	10	$\dot{\epsilon} = 8.49 \times 10^{-4} \sigma$	↓	↓
600	20	$\dot{\epsilon} = 2.12 \times 10^{-4} \sigma$	↓	↓
	50	$\dot{\epsilon} = 3.40 \times 10^{-5} \sigma$	↓	Climb
	100	$\dot{\epsilon} = 8.49 \times 10^{-6} \sigma$	↓	↓
	200	$\dot{\epsilon} = 8.90 \times 10^{-1} \sigma^{4.4}$	Climb	↓
	1	$\dot{\epsilon} = 4.86 \times 10^{-1} \sigma$	Coble	Coble
	2	$\dot{\epsilon} = 6.63 \times 10^{-2} \sigma$	N-H	↓
	5	$\dot{\epsilon} = 1.06 \times 10^{-2} \sigma$	↓	↓
600	10	$\dot{\epsilon} = 2.65 \times 10^{-3} \sigma$	↓	↓
	20	$\dot{\epsilon} = 6.63 \times 10^{-4} \sigma$	↓	↓
	50	$\dot{\epsilon} = 1.06 \times 10^{-4} \sigma$	↓	Climb
	100	$\dot{\epsilon} = 2.65 \times 10^{-5} \sigma$	↓	↓
	200	$\dot{\epsilon} = 3.28 \sigma^{4.4}$	Climb	↓

Nabarro-Herring

Fig. 5 Three-dimensional representation for the grain-size mechanism map

and very fine grain size; $1 \mu\text{m}$.

Positive effect of the temperature on creep strain can be noticed in the same figure. At a given stress level, the creep strain is higher for the fine-grained material than that for the coarse-grained material.

(a)

(b)

Fig. 6 Creep strain as a function of applied stress at different temperatures for coarse and fine-grained A3003P Al Alloy analysed by 2D FE analysis. Relations were determined at testing time of (a) 26 - 28 hr and (b) 196 hr

Figure 7(a) shows the time-strain relationship for the tensile creep specimens analysed under 0.637 MPa stress at 400°C for various grain sizes of the material. In Fig. 7(b), the relationship is drawn at the same load and grain size values but higher temperature, 600°C .

Temperature increase from 400 to 600°C shifted up the curves as the deformation mechanism has been changed. Looking at Fig. 7(c) clarifies that in spite of ten times increase in stress level; namely from

(a)

(b)

(c)

Fig. 7 Creep strain as a function of time for specimens tested analytically at (a) 400°C and 0.637 MPa, (b) 600°C and 0.637 MPa and (c) 500°C and 6.370 MPa

(a)

(b)

Fig. 8 Comparison between (a) compressive creep strain and (b) tensile creep strain resulted from the FE analysis at 400°C and 0.255 MPa.

0.637 to 6.370 MPa, the creep strain did not show any considerable differences comparable to those gained by temperature change shown in Fig. 7(b). It is very important to notice here that this comparison is made for grain size 1 μm .

Figures 8(a) and (b) show the creep strain in tension and in compression, respectively under the same test conditions (0.255 MPa, 400°C and 1–200 μm grain size). Creep strain in compression for both the fine and coarse-grained A3003P Al alloy showed same results to those analysed under tension. In other words, the parameters' effects on the creep strain are identical regardless the type of loading mode whether it is tension or compression. In this analysis, which based mainly on the grain-size mechanism and by using the FE program ABAQUS, loading mode could not show any effect on the creep behaviour for the material.

Table 2 Chemical composition of the A3003P aluminium alloy

Si	Fe	Cu	Mn	Zn	Al
0.6	0.7	0.05~0.20	1.0~1.5	0.1	Rest

(a) Tensile test specimen

(b) Compressive test specimen

Fig. 9 Test pieces used for experimental creep analysis (a) under tension and (b) under compression

4. Experimental Analysis

4.1 Specimen design and material

For both tension and compression test pieces the specimen designs are shown in Figs. 9(a) and (b), respectively. The same configuration used in the analytical investigation shown in Fig. 2 was applied for specimens tested under compression. Chemical composition for the material A3003P Al Alloy is shown in Table 2.

4.2 Test conditions

Specimens were tested under various stress and temperature levels. Loading mode was also changed between tension and compression. Grain size effect was not taken into consideration in the experimental analysis because of some technical restrictions (explained below) which made the grain size of material used in the plate fin limited to certain value (coarse grain size; 5 mm). Table 3 demonstrates the various test conditions applied in the experiments. All tests were held up to about 200 hr.

The temperature was monitored through the furnace thermometer and specimens were kept inside the furnace for 3 hr to assure the temperature stability and homogeneity throughout the specimen thickness. Displacement was measured using dial gauge with precision of 1/100 mm. Experimental apparatus and test machine are shown in Fig. 10.

Table 3 Experimental conditions

Material		A3003P Al alloy				
Dimension		14 ϕ × 60mm				
		Test Conditions				
Loading Mode	Compression	Applied stress (MPa)	Temperature (°C)			Time (hr)
			400	500	550	
		0.255	○	○	○	
		0.637		○		
		6.370	○	○	○	
		6.370	●	●	●

Fig. 10 Experimental creep test unit

As shown in Fig. 2, parting sheets (tube plates) cover the corrugated fins. Plates and fins are stacked together by brazing process. Brazing material used in this case is an aluminium alloy with 10% silicon. The liquid condition of the brazing material (Al-Si), which is in contact with fin, makes the silicon diffuses to it (the fin) easily. Excess diffusion of Si should be avoided because it deforms the shape of the fillet between the fin and plate. Diffusion process is likely to occur rapidly and in a faster way through the grain boundaries than in the grain matrix of the structure. This puts the limitations in using fine-grained structure for fin's material. The opportunity for increasing diffusion will be higher in that case. Therefore, it is usually recommended to keep the grain size as large as possible (5 mm as in this case) to minimise the occurrence of diffusion of Si to the fin, especially at high temperatures at which the plate fin is produced during the stacking/bonding process. With fine-grained structure, this problem is easily expected and damage in fin's shape would quickly happen.

Fig. 11 Specimen photography after creep test at 500°C showing the large grain size of the A3003P Al alloy

Grain size was tested only to keep its big size as 5 mm in average. One example of the grain size micrograph taken after test is shown in Fig. 11 where the average grain diameter measured was nearly constant before and after the test keeping the value of 5 mm.

5. Experimental Results

Time-strain relationships for the specimens tested under compression are shown in Fig. 12(a). In this figure, scattering in the data is clearly observed for stresses up to 0.673 MPa regardless the temperature level. The creep strain values for those cases do not show much differences in general. Considerable increase in creep strain can be noticed in the plot as the stress increases to 6.370 MPa. Those data are in good agreement with the analytical results previously shown in Fig. 6. In Fig. 12(a), the temperature change from 400 to 500°C has slight effect on creep strain either in case of stress level with 0.255 MPa or 6.370 MPa.

While the compressive creep strain at 6.370 MPa shows higher values than that obtained with lower stress level, the tensile creep strain at the same stress level (6.370 MPa) gives higher magnitudes as depicted in Fig. 12(b). Though the effect of loading mode detected by analytical investigations was null, yet the creep strain magnification shown in Fig. 12(b) opposes such results.

For more clarification, creep strain was plotted as a function of applied stress in both tension and compression in Figs. 13(a) and (b) at creep test time

Fig. 12 Comparison between creep strain for specimens tested (a) at various temperatures and stresses under compression and (b) under both tension and compression at 400°C and 6.370 MPa.

26 – 28 hr and 196 hr, respectively. Again, here it is revealed that the loading mode has great effect on creep strain regardless the misleading data of the specimen tested under 500°C and 6.370 MPa tensile stress.

Tensile creep strain is much higher than the compressive creep strain. At the same loading mode, which is compression here, the increase in stress level slightly increases the creep strain. This fairly agrees with analytical results shown in Fig. 6 excluding the stress level 6.370 MPa.

Fig. 13 Creep strain as a function of stress for specimens tested under both tension and compression. Data were determined at testing time of (a) 26 - 28 hr and (b) 196 hr

6. Discussion

6.1 Analytical prediction based on grain-size mechanism

Deformation mechanism changes as temperature, stress and/or grain size change. Referring to Fig. 5, which represents the deformation mechanism map of A3003P Al alloy at wide temperature range, the noticeable fact here is that ; as temperature increases, the Nabarro-Herring (NH) process becomes increasingly important at the expense of the Coble creep because the area occupied by this process (NH)

becomes much wider at higher temperatures. This makes the NH covers wider range of the material grain size as temperature increases as shown in Fig. 5. This phenomenon is valid for the deformation map up to certain point where the three mechanisms intersect. Behind this point (at much higher stresses) the mechanisms are considered to be in unbalanced condition and uncertain.

From the above mentioned explanation for the deformation mechanism map, it can be understood how the temperature change from 400 to 600°C greatly shifted the curves while no considerable change could be recorded in case of stress change as shown in Fig. 7(b) and (c).

6.2 Experimental results

The experimental results shown in Figs. 12 and 13 can be divided mainly into two main parts. One part illustrates the loading mode effect on creep strain. The other one shows the effect of temperature—in case of tension and compression mode—on creep strain and the effect of stress level on creep strain in case of compression.

Creep strain has shown higher values in case of tension than in case of compression as clearly illustrated in Fig. 12(b). This is in good agreement with previously reported data by Jansen and Dunand⁽⁸⁾. It is worth noticing that in Fig. 12(b), the tendency of both tensile and compressive creep curves are nearly identical. The differences are only in the creep strain values. It could be described as a characteristic behaviour of the material tested. Lack of experimental data either in the literature or in the current research concerning the compression creep test makes it difficult to confirm this conclusion.

Effects of both temperature and stress level on creep strain are shown in Figs. 12(a) and 13. Temperature effect on creep strain could not be detected regardless stress level applied except at the third stage of the creep curve where higher values were observed at 6.370 MPa compressive stress as shown in Figs. 12(a) and 13(b).

According to the grain-size mechanism, temperature change should be accompanied with creep strain change due to the change in the deformation mode as shown in Fig. 5. This is also declared through the governing equations of various deformation modes; Eqs.(1), (2) and (3). The grain-size mechanism was unable to accurately predict the creep behaviour for the aluminium alloy tested under tension and compression.

Stress level effect on creep behaviour showed better results concerning the analytical and experimental analyses. As shown in Figs. 6, 12 and 13 the effect of stress level on creep strain is obvious

Fig. 14 Comparison between the analytical and experimental creep strain for specimens tested at (a) 400°C and 0.255 MPa, (b) 500°C and 0.255 MPa, (c) 500°C and 0.637 MPa and (d) 500°C and 6.370 MPa

analytically and experimentally. The grain-size mechanism gives better anticipations in this case. Referring to Eqs.(1)–(6), it could be noticed the direct effect of the applied stress on the creep strain rate in Eqs.(1) through (3). In case of temperature, its effect is expanded through the parameters like D_i , G and D_{gb} in Eqs.(3) through (6), respectively. This is beside the main and direct effect of temperature on creep strain rate as shown in Eqs.(1) through (3).

More experimental work is still needed to fully establish the effect of stress level at different temperatures on creep strain, especially in case of compression stress. Moreover, the grain size effect on the creep behaviour could not be examined here for the technical restrictions mentioned above. As previously mentioned the average grain size for the material used was ≥ 5 mm.

6.3 Comparison between the Analytical and Experimental Results

Figure 14 summarises the results from the FE analysis compared with the experimental data. As mentioned above, the temperature effect on creep strain is considerable in the analytical analysis. In the same time it is worth mentioning that the grain size adopted in the experiments was 5 mm, this is considered as very coarse grain size. Deformation mechanism has great limitations concerning different parameters like the grain size, temperature and stress level. Above certain limits, the results have different records.

Deformation mode, according to the analytical model, does change with temperature, load and grain size but up to certain limits. These limitations make the creep strain and deformation mode estimation not accurate and far from the truth. It is clearly revealed in Fig. 14 how differences between the analytical

estimations and experimental findings increase as the temperature or load level increases.

Grain size effect can not be ignored as it has great role that influence the creep strain and deformation mode. The grain size limitations in this analysis to micrometers could not accurately predict the deformation mode of a material with grain size of millimetres.

7. On the Variation between the Analytical and Experimental Results

In present analytical study, it was shown that the creep strain decreases with increasing grain size. Experimental analysis could not investigate this effect because of using a 5 mm grain-size material due to the technical restrictions mentioned above. However, effect of grain size on creep rate was discussed before through the literatures^{(5),(8),(18)-(22)}. Whereas some data suggested that the creep rates decreased with increasing grain size, others suggested that the opposite trend was valid.

The analytical analysis is based on the deformation mechanism that mainly depends on the grain size effect upon the creep behaviour. It is worth mentioning that this model (grain-size mechanism)⁽⁹⁾ which used here was basically built on the data obtained from pure aluminium that tested under tension. This could explain the coincidence of the results obtained by FE analysis for cases tested under tension and under compression that shown in Fig. 8(a) and (b), respectively. The loading mode effect on creep behaviour can not be detected through the analysis using the model of grain-size mechanism⁽⁹⁾ in which the loading mode is mainly tension.

Experimental results presented here represents the Al alloy A3003P that tested under both tension and compression. Loading mode effect on the creep behaviour could play an important role in shifting the experimental results from the analytical predictions⁽⁸⁾.

Moreover, it has been shown by Servi and Grant⁽²⁾ that the impurities play an important role that affects the creep strain rate. It is anticipated that in the present study, the alloying elements in the A3003P contributed to the shifts noticed in the experimental results. This effect is missed in the theoretical approach (grain-size mechanism).

In the same time, it must not be forgotten that the grain size of the material (A3003P) tested in the experiments had an average value, which is considerably bigger than the biggest value applied in the analysis, of 5 mm as shown in Fig. 11. In spite of the grain size differences, there was an agreement, however in the general trend qualitatively and quantitatively between the analytical and experimental

Fig. 15 Grain size effect on deformation mechanism/creep strain when specimen is tested analytically using grain-size-based approach

results. Tensile creep strain showed higher values than that of the compressive creep.

Moreover, the analytical predictions for the creep strain under the compressive stress of 0.255 MPa and at 400°C coincide with the experimental results of the same conditions as shown in Fig. 14(a). At higher temperature; 500°C, the data are very near to the experimental findings as depicted in Fig. 14(b). Much differences were found with higher stress levels; 0.637 and 6.370 MPa regardless their temperature level; 500°C.

The question that may be raised here is: what about the grain size? Grain size for the material used in the experiments were about 5 mm or generally in the range of millimetres, while those of the analytical results for the same material were in the range of microns. Examining the deformation mechanism map used in this study⁽⁹⁾, and referring to Eqs. (1)–(3), it is found that the deformation modes NH and Coble are mainly dependent on the grain size, while the Climb creep is not. That can be clearly noticed from Fig. 15 which shows the creep strain as a function of grain size. This explains the limitation of the mechanism at specific grain sizes behind them the model can not predict the deformation mode. This limitation greatly affected the accuracy of the prediction in the analytical study especially at higher load levels where the deformation mode should be Climb. Role of grain size decreases as stress and temperature increase⁽²³⁾.

Though the variations between the analytical and experimental results seem to be developed from various sources, they (the sources) can be however, summarised in main two. First source is the material used

(chemical and mechanical properties), and the second is the loading mode (tension/compression). This conclusion strongly suggests having a theoretical modification to the existing deformation map to be used for different types of aluminium alloys under both loading modes; tension and compression and at various temperature levels. Further investigations are required in this direction for more verifications of the parameters' effect on creep behaviour in general.

8. Conclusion

Analytical and experimental investigations for creep behaviour of aluminium alloy A3003P tested under tension and compression were carried out. Study of parameters' effect on the creep behaviour using the two-dimensional finite element analyses was presented. Grain-size mechanism was applied in this analysis. Temperature, loading mode, stress level and grain size were the main parameters taken into consideration in this investigation. The current research could enlighten the research field with some important concluding remarks that are summarised below.

1. Tensile creep strain is higher than the compressive creep strain for all ranges of applied stresses and temperatures.

2. Compressive creep strain increases as load increases.

3. Creep strain is higher for the fine-grained material than that for the coarse-grained material at the same stress level.

4. Grain-size mechanism has a limited application. At high temperature and stress levels, it may be difficult to accurately predict the deformation mode by using the grain-size mechanism. Therefore, modification for the mechanism is strongly required.

5. Further investigations are necessary in this direction for more verifications of using the grain-size mechanism and for determining the parameters' effect on the creep behaviour in general.

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