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Variation of Strain Rate Sensitivity Index of a Superplastic Aluminum Alloy in Different Testing Methods

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Abstract. The strain rate sensitivity index, m-value, is being applied as a common tool to evaluate the impact of the strain rate on the viscoplastic behaviour of materials. The m-value, as a constant number, has been frequently taken into consideration for modeling material behaviour in the numerical simulation of superplastic forming processes. However, the impact of the testing variables on the measured m-values has not been investigated comprehensively. In this study, the m-value for a superplastic grade of an aluminum alloy (i.e., AA5083) has been investigated. The conditions and the parameters that influence the strain rate sensitivity for the material are compared with three different testing methods, i.e., monotonic uniaxial tension test, strain rate jump test and stress relaxation test. All tests were conducted at elevated temperature (470ºC) and at strain rates up to 0.1 s^{-1}. The results show that the m-value is not constant and is highly dependent on the applied strain rate, strain level and testing method.

INTRODUCTION

Polycrystalline materials with uniform tensile elongation above 200% are considered as superplastic. In general, superplastic forming is performed at high temperature (more than 0.4 of melting point) and at low strain rates (less than 10^{-2} s^{-1}) [1-3].

The deformation mechanism for superplastic metals greatly depends on the strain rate [4-5]. In order to evaluate the time dependency of mechanical properties, the strain rate sensitivity index, m-value, has been introduced. The index is defined as [6]:

$$m = \left. \frac{\partial \ln(\sigma)}{\partial \ln(\dot{\varepsilon})} \right|_{\varepsilon} \tag{1}$$

where σ is the true stress and $\dot{\varepsilon}$ is the strain rate. The m-value is an essential parameter when modeling material behaviour in the numerical simulation of superplastic forming processes [7-9]. For instance, a power law-type equation is one of the most referred to models [2]:

$$\sigma = K\varepsilon^{n}\dot{\varepsilon}^{m} \tag{2}$$

where K is a constant, ε is strain and n is the strain hardening exponent. The strain rate sensitivity index, m, is commonly assumed to be independent of strain, strain rate and testing method (i.e., it is considered to be a constant number in Eq. 2).

The m-value of a sheet metal is usually measured via monotonic uniaxial tension tests at various strain rates, strain rate jump test, or stress relaxation tests [3, 6 and 10].

Both average and instantaneous strain rate sensitivity indices could be measured from uniaxial tension tests when stress levels at different strain rates are measured at the same strain value. The average m-value could be defined from the slope of the logarithm of stress versus logarithm of strain rate. However, based on Eq. 1, in order to measure instant m-values, ln(σ) is differentiated against $\ln(\dot{\varepsilon})$.

In a strain rate jump test, the sample is pulled initially up to a predefined strain with a given strain rate ($\dot{\varepsilon}_1$). Then the strain rate (the cross-head velocity) is suddenly increased to higher stress level ($\dot{\varepsilon}_2$). Thus, in this method, the need for several uniaxial tensile tests is reduced to a single test. By measuring the stress levels corresponding to each strain rate just before and after the jump, i.e., σ_1 and σ_2, one can find the m-value as [3, 11]:

$$m = \frac{log\left(\sigma_2/\sigma_1\right)}{log\left(\dot{\varepsilon}_2/\dot{\varepsilon}_1\right)} \tag{3}$$

In a stress relaxation test, the sample is pulled up to a predefined strain and the motion of the crosshead is momentarily stopped for a certain period at that strain. During this period, the strain rate is equal to zero and the stress level tends to decrease rapidly. The advantage of this method is the ability to measure the m-value via a single test regardless of selecting the strain or strain rate level [10]. Several approaches have been proposed in order to determine the m-value from a stress relaxation test [3, 10]. One of the most employed methods is to obtain the average m-value from the inverse of the slope of the line passing the ln(σ) against $\ln\left(-\dot{\sigma}\right)$, according to the following equation [6]:

$$\frac{d\ln\left(\sigma\right)}{d\ln\left(-\dot{\sigma}\right)} = \frac{1}{m} \tag{4}$$

It has been reported that for superplastic alloys, the m-value is not constant and it changes with strain rate variation and temperature [1-3]. Nevertheless, the impact of the testing variables on the measured m-values has not been taken into consideration. However, it is reasonable to assume that small changes in material composition or the use of different testing methods could impact the measured m-value and the lack of a systematic study where the same material with the same sample geometry, testing equipment and measurement devices (e.g., test press, extensometers, etc.) is evident.

In this study, the above parameters are taken into account and the influence of testing method, with other parameters being conditions and the parameters that influence the strain rate sensitivity index are considered. The generation of such comparable data will allow one to better gauge the accuracy and reliability of the measured values and, as a direct consequence, will have a marked impact on the reliability of simulation models where 'm' is used as an input.

MATERIALS AND METHODS

In order to measure the strain rate sensitivity, three different methods (i.e., monotonic loading at three strain rates, strain jump test, and stress relaxation test) were used on samples prepared according to the ASTM 2448 standard [11]. The material used for the testing was AA5083 sheet with thickness of 1.06 mm taken in the rolling direction. The test conditions are summarized in Table 1. All the tests were conducted in an MTS 100-kN servo-hydraulic machine at 470ºC. An MTS environmental heating chamber, model 651, was utilized to achieve the required temperature. The temperature of the sample was monitored by two K-type thermocouples placed at the surface of sample near the grips.

The monotonic uniaxial tension test was conducted at three strain rates: 0.001, 0.01 and 0.1 s^{-1}. As shown in Fig. 2, the average m-value was measured from the slope of the linear fitting while the instantaneous m-value represents the tangent of the nonlinear fitting (the red line in Fig. 2).

For the strain rate jump test, depending on the applied strain rates and the number of jumps, six tests were carried out. The details of each test are presented in Table 1 and Fig. 2. For these tests, the m-value was determined according to Eq. 3 and the stress levels were measured just before and after each strain rate jump.

The stress relaxation tests were conducted for strain rates of 0.001, 0.01 and 0.1 s^{-1}. In each test, the relaxation was applied four times at plastic strain levels equal to 0.05, 0.2, 0.35 and 0.5, and the stress variation during each relaxation period was analyzed. As shown in Fig. 3, the stress level rapidly decreased to around zero. Data smoothing was carried out using the OriginLab® software and the first derivative of stress with time (i.e., $\dot{\sigma}$) was calculated. Finally, the average m-value was calculated by linear approximating of ln(σ) vs. $\ln\left(-\dot{\sigma}\right)$, according to Eq. 4.

The instantaneous m-values calculated in monotonic tension tests from the stress at the beginning of the plastic deformation (i.e., plastic strain equal to zero) are presented in Fig. 4 as a function of the strain rate and plastic strain. According to Fig. 4(a), the maximum m-value was observed at a strain rate equal of 10^{-3} s^{-1}. It can also be seen in this figure that the m-value decreases by 20% and 40% as the strain rate increases from 10^{-3} to 10^{-2} and 10^{-1} s^{-1}, respectively. Moreover, as shown in Fig. 4(b), at constant strain rates, the m-value depends on the plastic strain level. For instance, at a strain rate of 10^{-3} s^{-1}, the m-value declines by 44% as plastic deformation increases from zero to 0.6. The average m-values also follow the same trend where increasing the plastic strain from zero to 0.8 decreases the m-value by 45%. According to this figure, the average m-values are close to the instantaneous m-values for strain rate of 10^{-2} s^{-1}. These results show that both the average and instantaneous m-values are not constant with strain and, therefore, assuming a constant number for the entire range of plastic strain in viscoplastic models (for instance Eq. 2) is not an accurate assumption.

As shown in Fig. 2, whenever the strain rate is suddenly increased to over 0.001 s^{-1}, a peak in the flow curve is observed. This behavior can be explained by the kinetics of dislocations multiplication [12]. A sudden increase in the strain rate causes an abrupt rise in stress due to the acceleration of mobile dislocations, while the density of dislocations remains almost constant. The size of the stress peaks is controlled by internal friction stress, the adjustment rate of dislocations pile up, or the short range displacement of dislocations between soft and hard regions in the microstructure [12].

TABLE 1. The test conditions in this study.

Test Number	Test Method	Strain Rate (s^{-1})	Number of Jumps/Relaxations
1	Monotonic uniaxial tension	0.001, 0.01 & 0.1	-
2	Strain rate jump	0.001 & 0.1	3
3	Strain rate jump	0.001 & 0.01	3
4	Strain rate jump	0.0001 & 0.001	2
5	Strain rate jump	0.0001, 0.0005 and 0.001	6
6	Strain rate jump	0.001, 0.01 and 0.1	4
7	Strain rate jump	0.0001, 0.0005, 0.001, 0.005 and 0.01	4
8	Stress relaxation	0.001	4
9	Stress relaxation	0.01	4
10	Stress relaxation	0.1	4

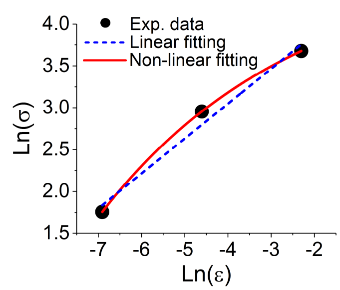


FIGURE 1. The ln(σ) *vs* $\ln(\dot{\varepsilon})$ at onset of plastic strain (Test 1).

RESULTS AND DISCUSSION

In order to avoid any calculation error due to the local peaks, the flat region in flow curve after each jump was extrapolated by a line. The intersection of this line with a vertical line at the onset of jump was considered as the new stress level (i.e., σ_2). As shown in Fig. 5, the m-values calculated from various strain rate jump tests, vary with the test parameters. In Fig. 5(a), at the strain level of 0.05, the strain rate sensitivity depends on the level of the strain rate before and after the jump. For instance, with the same initial strain rate of 0.001 s^{-1}, the m-value is smaller when the subsequent strain rate is 0.1 s^{-1} (Test 2) rather than when it is equal to 0.01 s^{-1} (Test 3). The same behavior could be seen from Fig. 5(b), where the m-values calculated from Test 5 ($\dot{\varepsilon}$:10^{-4}, 5×10^{-4} and 10^{-3} s^{-1}) and Test 7 ($\dot{\varepsilon}$:10^{-4}, 5×10^{-4}, 10^{-3}, 5×10^{-3} and 10^{-2} s^{-1}) are almost identical up to strain of 0.2 since the test procedures were identical up to this strain. However, when the subsequent jumps occur at higher strain levels (i.e., 0.3 and 0.4), the m-values are not identical because the two tests follow different paths (the initial and subsequent strain rates are different). The above results clearly show that the impact of strain rate on m-value is not explicit in strain jump tests and one cannot yield a straightforward relationship between the m-value and strain rate using this test. Therefore, care must be taken when using m-values obtained from strain rate jump tests.

The above findings were further investigated by analyzing the impact of the test history on the m-value calculated from strain jump tests. For this purpose, the results from Tests 3 and 6 were compared (Fig. 6). As shown in Figures 2(b) and 2(e), both tests started with a strain rate jump from 0.001 to 0.01 s^{-1} at a plastic strain of 0.05. As shown in Fig. 6, the calculated m-values for the two tests are identical at this strain. But from this value, and up to a strain of 0.3, the test parameters became different and, as shown, the m-values follow different trends. At a strain level of 0.3, the two tests return to the same condition, where the strain rate drops from 0.01 to 0.001 s^{-1} (see Fig. 2(b) and (e)). At this strain, regardless of the history of the test, the m-values are identical. These results appear to indicate that the m-value calculated from strain rate jump test depends only on the strain and strain rates employed but not on the deformation history. This finding is very interesting; however, further experiments with other materials and other combinations of strain and strain rate jump tests are required to fully characterize this behavior.

In Fig. 6, the dashed lines represent the m-value measured from the uniaxial tension tests at various strain rates. There is a discrepancy between the results from the two methods. It can be seen that contrary to the uniaxial tension test, m-values calculated from the strain rate jump test do not follow a gradual reduction trend with increasing the plastic strain. The observed differences could be explained by the nature of the two tests: in uniaxial tension test, it is possible to separate the impact of strain rate from strain, while in the case of a strain rate jump test, one cannot exclude the impact of strain rate on the m-value from the impact of strain on the results.

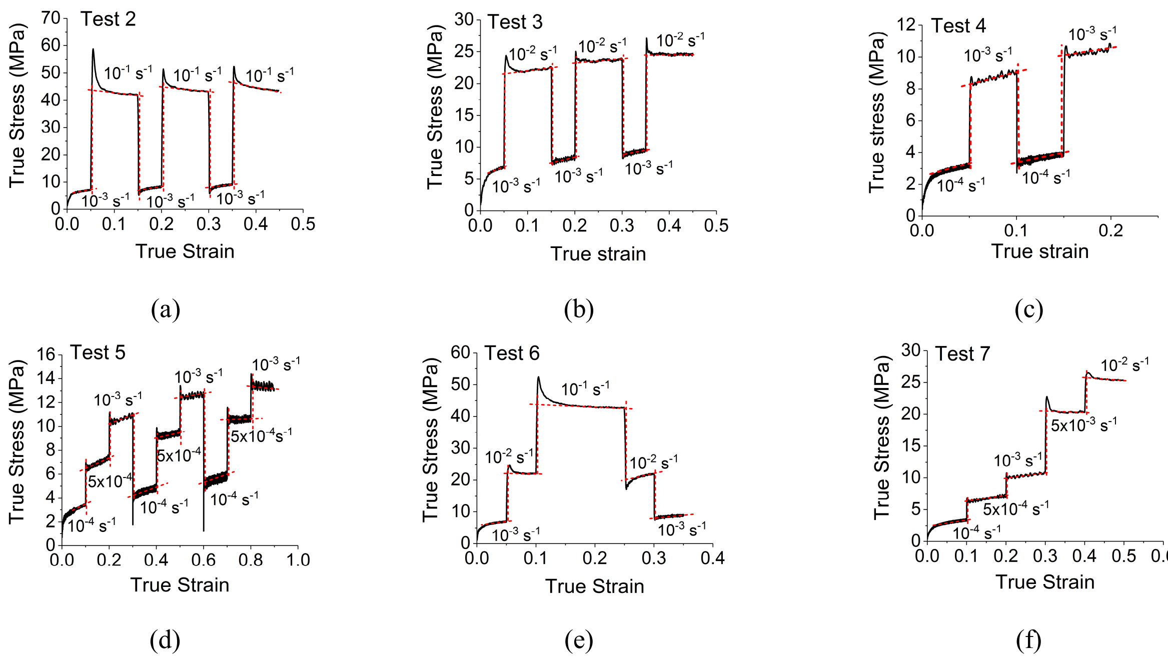


FIGURE 2. Stress vs. strain at different strain rate jump tests according to: (a) Test 2, (b) Test 3, (c) Test 4, (d) Test 5, (e) Test 6 and (f) Test 7.

The results from the stress relaxation tests are summarized in Fig. 7. Compared with the results calculated from uniaxial tension tests (the dashed lines), the m-values are overestimated with this method. In addition, this figure shows that, by increasing strain and strain rate, the m-value increases, which is in contrast with the results obtained from the uniaxial tension tests (Fig. 4). The observed differences could be attributed to the very low stress levels that need to be measured during the stress relaxation test for this material. The stress relaxation tests indicated stress levels in the range of less than 1 MPa which were at the resolution limit of the load cell employed in this investigation. Therefore, while the application of the stress relaxation method cannot be ruled out for estimating the m-value; it is likely that it is not a proper method for measuring it for the studied material unless very low capacity and high resolution load cells are used.

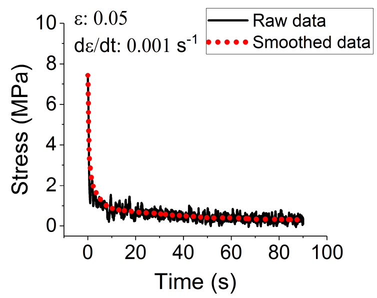
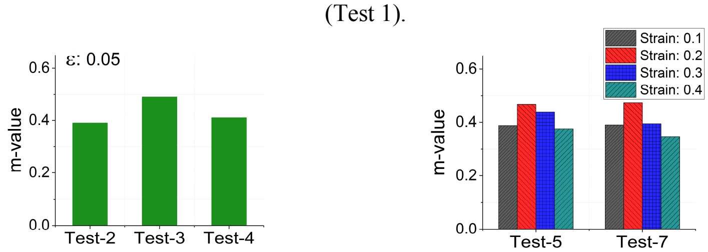


FIGURE 3. Stress vs. time during a relaxation period (Test 8).

(a) (b)

FIGURE 4. Instantaneous m-value as a function of (a) strain rate and (b) plastic strain, calculated from monotonic tensile test (Test 1).



(a) (b)

FIGURE 5. The m-values calculated from strain jump tests: (a) for Test-2, Test-3 and Test-4 at strain equal to 0.05, (b) for Test 5 and Test 7 at strains equal to 0.1, 0.2, 0.3 and 0.4.

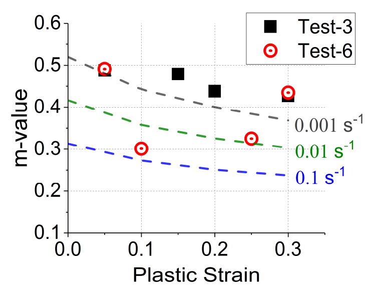


FIGURE 6. m-value vs. plastic strain for two strain jump tests (Test 3 and Test 6).

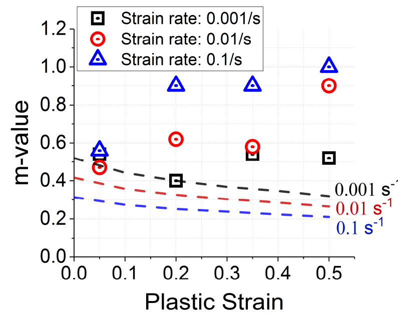


FIGURE 7. Variation of m-value with plastic strain for stress relaxation tests

CONCLUSIONS

The strain rate sensitivity index varies with strain rate and strain level and, therefore, should not be considered as a constant number in constitutive models.

For the studied material, by increasing the strain rate and plastic strain, the m-value decreases. By increasing the plastic strain, the average m-value decreases by about 45%. The testing method and calculation scheme have a significant impact on the results. The m-values calculated from the strain rate jump tests depend on test parameters.

Compared with the monotonic uniaxial tensile tests, the strain rate jump test and stress relaxation method require minimum experimentation for assessing the m-value. Nevertheless, in the present study, in order to study the impact of strain and strain rate on m-value, monotonic uniaxial tension tests at various strain rates could successfully provide feasible results while it was not possible to conclude an explicit relationship between the m-value and strain rate from the strain rate jump test. Also, the application of stress relaxation test for assessing the m-value was questionable, most likely due to the equipment limits.

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