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ON THE EXISTENCE OF THRESHOLD STRESS

F. Booeshaghi and H. Garmestani
FAMU-FSU College of Engineering, Department of Mechanical Engineering and Center for Materials Research and Technology (MARTECH), Tallahassee, FL 32310-2175

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Introduction

Recently, several studies of conventional superplasticity and high strain-rate superplasticity (HSRSP) have illustrated the concept of threshold stress (1–4). In one such study, Bieler, Mishra, and Mukherjee (5) observed that some aluminum based materials subjected to HSRSP, for a given range of temperatures, have the same log (σ) − log ($\dot{\varepsilon}$) behavior as conventional superplastic alloys. Hence, a true understanding of the material's behavior in region I, which is known as the region where the threshold stress exists, is important to fully characterize superplastic materials.

In general, the threshold stress, σ_0, is used to explain the decay in the strain-rate sensitivity index in region I. Due to lack of experimental data in the very low strain-rate regimes, the researchers use extrapolation techniques to calculate the values of the apparent threshold stress (3,5–7). The threshold stress, σ_0, typically appears in the flow stress, σ, versus strain-rate, $\dot{\varepsilon}$, relationship as shown in Equation (1).

$$\dot{\varepsilon} = A(T,d, \cdots)(\sigma - \sigma_0)^n. \tag{1}$$

In this equation, $A(T, d, \ldots)$ is a coefficient dependent on the temperature, T, grain size, d, and other material parameters, and n is the inverse of the strain-rate sensitivity index ($m = 1/n$).

In this paper theories concerning the existence of threshold stress are questioned and in light of new experimental results their validity are examined. Several observations made during a detailed characterization of superplastic aluminum alloys are presented. Using a new unified phenomenological model the transitional behavior of region I to region 0 is explained.

A Brief Background on Mechanical Testing Methods

Test methods used to characterize the inelastic flow of materials rely on the control of either displacement (rate), load (rate), or some variation of these two parameters (i.e., true strain, stress, inelastic strain, etc.). These attempts are directed towards finding a relationship between the inelastic strain rate, $\dot{\varepsilon}$, and the applied stress, σ, at varous strains and temperatures. Constant strain-rate, strain-rate change and creep tests are predominantly used to characterize superplastic materials, none of which could correctly provide information in the very low strain-rate regions (8). The most widely used technique in the superplasticity community is the strain-rate change test (9–11). The shortcoming of this test is that it only explores the upper region of the strain-rate history (approximately greater than 10^{-5}

s^{-1}) due to machine limitations. The constant strain-rate test is also used (12,13). The problems with this test are that it requires large plastic deformations which result in hardening, many tests are needed to characterize a single material, and it still cannot explore the very low strain-rate regions. The possibility of changes in the microstructure, such as hardening, are the main reasons for lack of popularity of the creep test in characterizing superplastic materials.

In 1973, Hart and Solomon (14) proposed that load relaxation test could be used to characterize materials over a wide range of strain-rates. Load relaxation tests cover the determination of the time dependence of stress in materials and structures under conditions of approximately constant constraint, constant environment, and negligible vibration. In this test, the material is initially constrained by an externally applied force and the change in the applied force necessary to maintain the constraint is determined as a function of time. Even though the rate of change of total strain with respect to time is zero, deformation of material from the elastic strain to inelastic strain follows a load-time history. This relationship is mathematically related to the inelastic strain-rate of the deformation process (15). It is necessary to note that the concept of load relaxation test is a very simple one but the test itself is very sensitive and should be performed under extreme control of the environment's temperature. The reproducibility of data will depend on the manner in which all test conditions are controlled. A lack of temperature controllability will result in unexplainable results at low flow stress levels (9).

Experimental Procedure

The material used for this investigation is statically recrystallized Al-7475 with nominal composition of Al − 5.7% Zn − 2.3% Mg − 1.5% Cu − 0.22% Cr. Dog bone shaped test samples were cut from rolled sheets parallel to the rolling direction. The dimensions of the sample were: gage length = 14.93 mm, width = 2.83 mm, and thickness = 2.46 mm. Extreme caution was employed during machining to avoid introducing surface defects.

Two types of mechanical tests, load relaxation and strain-rate change tests, were employed. The tests were performed using a screw driven load frame equipped with a standard interchangeable load cell with accuracy of ±0.1% and a three-zone clamshell type resistance furnace with a sensitivity of ±0.5°. The test temperatures were 400°C, 450°C, 477°C, 516°C, and 525°C and applied strain-rates were $5 \times 10^{-4}\ s^{-1}$, $5 \times 10^{-3}\ s^{-1}$, $5 \times 10^{-2}\ s^{-1}$, and $5 \times 10^{-1}\ s^{-1}$. The entire test system was placed inside a test chamber to prevent from environmental effects.

Results and Discussion

Threshold Stress Analysis

In the past investigations a lack of experimental data in the lower strain-rate regimes coupled with a transitional decrease of the strain-rate sensitivity index from region II to region I has resulted in an assumption of the existence of a threshold stress (4). To account for the existence of this apparent threshold stress, various extrapolation schemes have been developed (3,5,7). One common method involves plotting $\dot{\varepsilon}^{1/n}$ versus σ on linear scales and extrapolating the data to zero strain-rate using linear regression (5). The threshold stress value is determined from the intercept with the stress axis. Since the value chosen for n influences the assumptions of the active deformation mechanisms in the lower strain-rate regime, a value of n that fits the data the best is customarily used.

In the following the partiality of this extrapolation technique to enforce an apparent threshold stress is studied. Figures 1 (a) and 1 (b), show the variation in the calculated threshold stress in terms of temperature for $n = 2$ and $n = 3$, respectively. The threshold stress calculated for various n values are

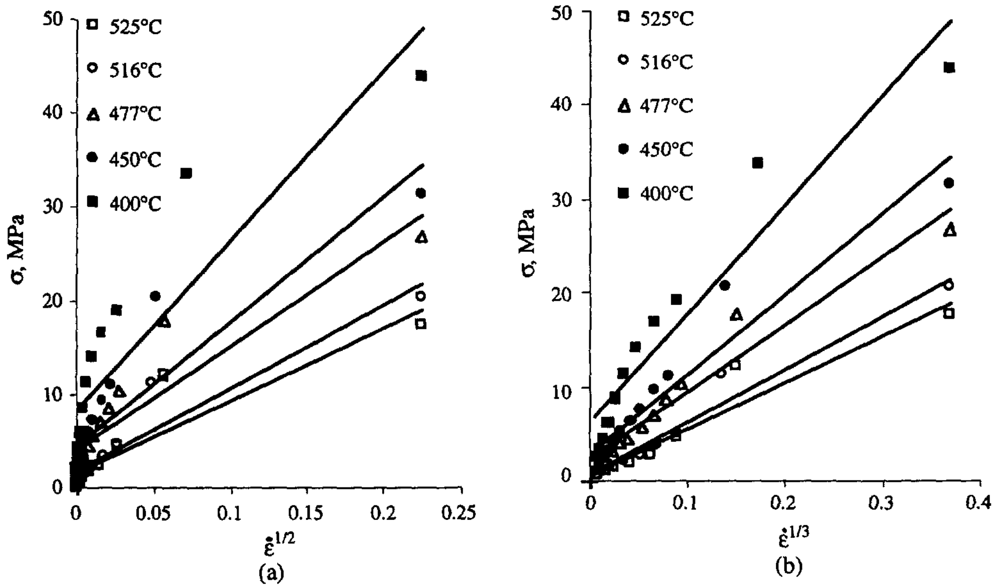

Figure 1. Threshold stress analysis for Al-7475 at various temperature regimes where a) $n = 2$ and b) $n = 3$.

tabulated in Table 1. These values reinforce the observation of others that the threshold stress strongly depends on the temperature (2,5,7,16). The threshold stress clearly decreased with increase in temperature for Al-7475. For $n = 4$ negative values were found for the threshold stress at 477°C and above, and for $n = 5$ all calculated values for the threshold stress were negative. This indicated that the assumption for the stress exponent value of 2 or 3 would lead to an apparent threshold stress for this material.

Once a threshold stress is found it is commonly used to regenerate the log stress versus log strain-rate curves based on the effective stress, $\sigma - \sigma_0$ (6). The new plots always favor the behavior that was introduced by the choice in n [5]. This assumption creates an artifact that resembles a continuous decay in the strain-rate sensitivity and an eventual limiting of a threshold stress.

Log (σ)-Log ($\dot{\varepsilon}$) Curves

Figure 2, shows the behavior of Al-7475 at various temperature levels. The experimental data cover over seven decades of strain-rates. At 400°C the material was visibly out of superplastic temperature range and very little grain boundary sliding was observed. This was evident by a lack of clearly defined

TABLE 1
Calculated Values for the Apparent Threshold Stress (MPa) for Various n Values. (Negative Values Indicate an Implausible Choice for n)

	400°C	450°C	477°C	516°C	525°C
n = 2	8.42	4.62	4.26	1.96	1.89
n = 3	6.16	2.85	2.42	0.57	0.66
n = 4	2.43	0.30	0.01	−0.94	−0.73
n = 5	−0.73	−1.96	−2.13	−2.32	−2.01

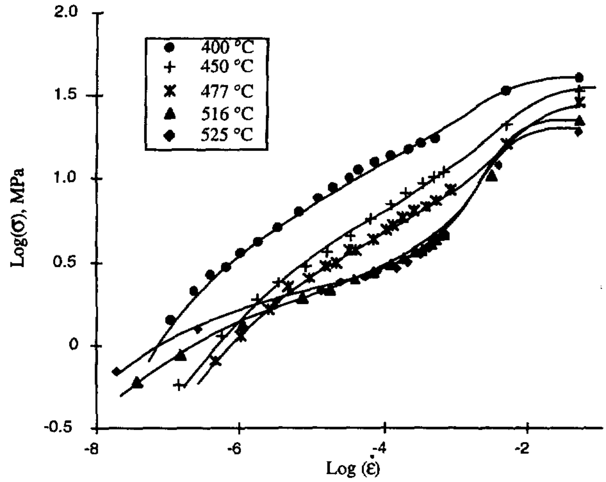

Figure 2. Experimental results (Al-7475) Vs. MHM (solid lines) at elevated temperatures (8).

region II. A shift to lower flow stress levels for given strain-rates was observed at 450°C. The level of grain boundary sliding had increased somewhat, but the material still did not behave superplastically. The material's behavior at 477°C, the eutectic temperature, was similar to that at 450°C with the exception of a slight shift in the curve to the higher strain-rate regions. Regions 0, I, II, and III were clearly visible for 516°C. This indicated that 516°C was within the range of temperatures that this material was superplastic. At this temperature, the grain boundary sliding region, region II, expanded from $5 \times 10^{-5}\ s^{-1}$ to $5 \times 10^{-3}\ s^{-1}$, and the strain-rate sensitivity index, m, equaled to 0.65, which was at its highest.

In region I at a strain-rate of approximately $5 \times 10^{-5}\ s^{-1}$, a change in the concavity of the curve, from concave up to concave down, was observed. This observation rejected the notion that a threshold stress exist for this material. During the transition from region I to region 0, at 516°C, the strain-rate sensitivity increased sharply and reached a value of 0.5 at $5 \times 10^{-8}\ s^{-1}$. This behavior led to the notion that the high value for strain-rate sensitivity in region II may be a local maxima and the strain-rate sensitivity index may grow to a global maximum at much lower strain-rates. The material also showed superplastic behavior at 525°C and regions 0, I, II, and III were clearly visible. Region I expanded over a wider range of strain-rates than the one for 516°C, and also showed a shift in the curve to the higher stress levels in region 0.

Modeling Efforts

The modified Hart's model (MHM) (17) was used to simulate the behavior of this material at various temperatures and strain-rate regimes (Figure 2). The model completely predicted the behavior of superplastic Al-7475 for both superplastic temperature and strain-rate and non-superplastic temperature and strain-rate regimes. The mathematical formulation for this model is shown below:

$$\sigma = y\sigma_s + (1 - y)\sigma_m \tag{2}$$

$$\dot{\varepsilon} = \dot{\varepsilon}_s + \dot{\varepsilon}_m \tag{3}$$

The subscripts m and s designate matrix and grain boundary sliding components, respectively. Equations (2) and (3) are the kinematics equations describing the constraints imposed by the sliding

TABLE 2
The Parameters of MHM for Al-7475 Deformed at 400°C, 450°C, 477°C, 516°C, and 525°C

T, °K	λ	σ^*, MPa	$\dot{\varepsilon}^*$	y	σ_s^0, MPa
400	0.17	61	5.88E-7	0.45	1.0E+4
450	0.17	41	5.80E-7	0.59	8.0E+3
477	0.17	35	4.90E-7	0.62	6.0E+3
516	0.17	25	4.00E-8	0.84	4.6E+3
525	0.17	21	2.00E-8	0.86	4.1E+3

mechanism where σ is the flow stress, $\dot{\varepsilon}$ is the inelastic strain-rate, σ_s and σ_m are the portions of the flow stress contributing to GBS and matrix deformation, respectively, $\dot{\varepsilon}_s$ and $\dot{\varepsilon}_m$ are the inelastic strain-rates due to GBS and matrix deformation, and the parameter y is the area fraction of the sliding region. The scalar relationships among the parameters of the model are shown in equations (4) and (5), where σ^* is the hardness parameter (dislocation density), $\dot{\varepsilon}^*$ is the material parameter dependent on σ^*, λ is the shape factor, m and f are phenomenological parameters, G is the shear modulus, Q is the apparent activation energy, R is the gas constant, and T is the absolute temperature.

$$\ln \sigma_m = \ln \sigma^* - \left(\frac{\dot{\varepsilon}^*}{\dot{\varepsilon}}\right)^{\lambda} \tag{4}$$

$$\dot{\varepsilon}^* = (\sigma^*/G)^m f \exp(-Q/RT). \tag{5}$$

The parameter σ_s is related to the microstructure as,

$$\sigma_s = \sigma_0^s(T,d,\delta,D_g,p,b)\dot{\varepsilon}_s. \tag{6}$$

Where, σ_0^s is the grain boundary sliding coefficient and it is a function of T the absolute temperature, d the grain size, δ the grain boundary width, D_g the grain boundary diffusion coefficient, p the grain size exponent which is usually around 2–3, and b the Burgers vector. In these formulations, it is assumed that $\dot{\varepsilon}_s$ and $\dot{\varepsilon}_m$ have equal weights. The MHM is the first model of its kind that can accurately simulate region 0.

The phenomenological parameters of this model are listed in Table 2. The parameter λ, which is known as the shape factor, had a constant value of 0.17 for all ranges of temperature. The parameter σ^* is the material hardness and represents the density of immobile dislocations, forest dislocations, and dislocation tangles. The hardness decreased as the temperature increased which indicated the activation of a recovery process. The parameter $\dot{\varepsilon}^*$ is dependent on the hardness and followed the same inverse relationship with temperature. In contrast, y which is associated with the level of grain boundary sliding during superplastic deformation was observed to be directly affected by changes in temperature. The dependence of this parameter on temperature is currently under study. The parameter σ_s^0 which is related to the presence of grain boundary sliding in terms of strain-rate decreased with an increase in temperature.

Conclusions

Superplastic Al-7475 was investigated at 400°C, 450°C, 477°C, 516°C, and 525°C and strain-rates of $5 \times 10^{-4}\ s^{-1}$, $5 \times 10^{-3}\ s^{-1}$, $5 \times 10^{-2}\ s^{-1}$, and $5 \times 10^{-1}\ s^{-1}$. Load relaxation and strain-rate change tests were utilized for mechanical characterization. Regions 0, I, II, and III of log σ versus log $\dot{\varepsilon}$ were observed at superplastic temperatures. At 516°C, the maximum strain-rate sensitivity in region II was

0.65. The strain-rate sensitivity index in region I at first decayed exponentially resembling the existence of a threshold stress but the transition to region zero was followed by an increase in its value. The high value in strain-rate sensitivity index observed may be a local maxima for this material, and there may be other strain-rate regions where the strain-sensitivity index is greater than 0.65. Based on the observed behavior we conclude that a threshold stress does not exist for this material. Region I, which is known as the threshold stress region, is only a transitional region between regions II and 0. The fact that it may extend over two to three decades of strain-rate may signify the nature of such transition. This was clearly shown in the data presented in this paper. If this region is not included completely, it creates the impression that region I extends indefinitely and a threshold stress may exist. This would wrongfully lead to the use of various extrapolation schemes to account for the apparent threshold stress.

Acknowledgments

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