COMPARISON OF SOLID AND TUBULAR SPECIMENS IN HOT TORSION TESTING OF AN ALUMINIUM ALLOY

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ABSTRACT The present work compares the flow behaviour of solid and tubular cylindrical torsion specimens. Thermal gradients of maximum 6°C are observed at the surface of the gage section in both geometries. These gradients are due to inhomogenities in the heat input and heat-diffusion into the shoulder of the specimens. Heat generated during deformation probably increases the gradients but this has no influence on the deformation in the gage section. The deformation seems to be uniform. The strain rate sensitivity and the activation energy of the hot deformation process have been calculated and the steady state flow stress for both massive and tubular specimens have been compared. The strain rate sensitivity, m, for the solid specimen was found to be 0,196, 0,204 and 0,214 at 400°C, 500°C and 570°C, respectively. The values for the tubular specimen was approximately 7 % lower at all temperatures. The activation energy of deformation, Q, was 180 kJ/mole for tubular specimens and 160 kJ/mole for solid specimens. The reason for the different strain rate sensitivity and activation energy is that the flow stress in tubular specimens over-estimates that of the solid specimens at low strain rates. This is most likely due to distortion of the flow behaviour by the mandrel when buckling of the wall in the tubular specimen take place. This gives a value of the torque which is higher than the real value and it seems that this effect increases with decreasing strain rate.
Keywords: *hot deformation, torsion test*

1. INTRODUCTION

The torsion testing method is frequently used to determine plastic flow behaviour of materials at high temperatures. Twisting a circular cylinder has the advantage of experimental simplicity and it is easy to achieve large strains without introducing undesireable global deformation like necking and barreling. The disadvatage is that such a specimen is nonuniformly loaded which lead to complication in defining the stresses. Attempts have been made to avoid the nonuniform loading by using tubular specimens. In a tubular geometry the effect of stress, strain and strain rate gradients along the radius are minimized, but in thin-walled specimens global deformation again becomes a problem.

The scope of this work is to compare the flow behaviour of solid and tubular torsion specimens.

2. THEORETICAL BACKGROUND

The torque, M, applied to a circular cylinder is given by the integral:

$$M = \int_{r_i}^{r_o} 2\pi r^2 \tau dr \qquad (1)$$

where τ is the shear stress at the radius r and r_i and r_s are the inner and surface radius, respectively. If it is assumed that strain is proporsional to the radius and stress is proporsional to the strain, the integration results in the so-called quasielastic solution [1,2,3]. The surface stress in a tubular specimen is then given by:

$$\tau_s = \frac{2r_s M}{\pi(r_s^4 - r_i^4)} \qquad (2)$$

The full plastic solution [1,2,3] is obtained if it is assumed that the stress is uniformly distributed across the wall-thickness,

$$\tau_s = \frac{3M}{2\pi(r_s^3 - r_i^3)} \qquad (3)$$

Equation 2 and 3 are considered to be the upper and lower bounds, respectively, for the surface stress in a tubular torsion specimen. Another approach is to assume that the shear stress at any radius is related to the shear strain and shear strain rate at that radius as:

$$\tau = K\gamma^n \dot{\gamma}^m \qquad (4)$$

where K is a constant, n is the strain hardening exponent and m is the strain rate sensitivity. Both n and m are assumed to be constant and not dependent on the radius. At low temperatures the strain rate sensitivity is low (m=0) while at high temperatures the effect of strain hardening can be neglected (n=0) [5,6,7]. Introducing this expression into Eq. 1 one obtains:

$$\tau_s = \frac{M(3+n+m)}{2\pi r_s^3\left(1-\left(\frac{r_i}{r_s}\right)^{3+n+m}\right)} \qquad (5)$$

For a solid specimen r_i=0 and this equation yields the result of Fields and Backhofen [4]. In converting from shear stress and shear strain to equivalent stress and strain the vonMises flow criteria has been used. n and m can be estimated from the Eq. 6 and 7 where ω is the angular velocity:

$$n = \left|\partial \ln M / \partial \ln \theta\right|_{\omega,T} \qquad (6)$$

$$m = \left|\partial \ln M / \partial \ln \omega\right|_{\theta,T} \qquad (7)$$

3. EXPERIMENTAL

The torsion experiments were carried out on an AlZnMg-alloy containing 4,5 wt% Zn, 0,8 wt% Mg, 0,03 wt% Si and 0,07 wt% Fe. The material was homogenized at 490°C for a period of 6 hours. The torsion specimens were machined from a Ø203 mm DC-cast billet with the axis of the torsion

specimens perpendicular to the casting direction. The gage length and the surface radius of each specimen were 10 mm and 5 mm, respectively. The tubular specimens had an inner radius of 3 mm, i.e. the wall-thickness was 2 mm, and in these specimens a mandrel (i.e. a core) with a radius of 2,9 mm, Figure 1, was used. The specimens were induction heated and the power supply to the

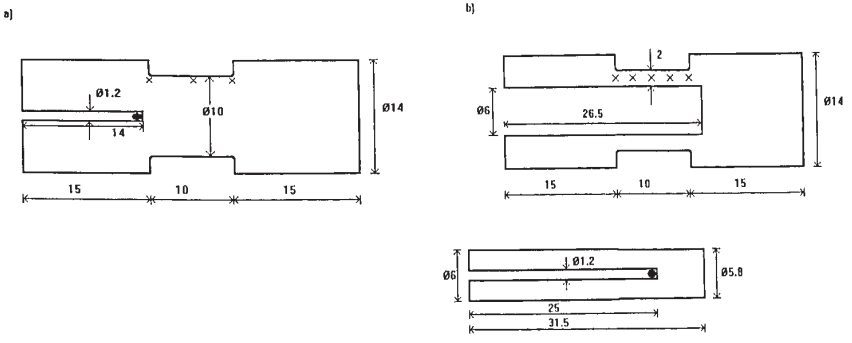

Figure 1 a) Solid specimen, b) Tubular specimen and the mandrel which was placed into the tube during testing. •= temperature control position. x=position for temperature measurments. All numbers in mm.

induction coil was controlled by a thermocouple. The thermocouple was positioned 1 mm from the gage section at the center axis in the solid specimens and in a position in the mandrel corresponding to the center of the gage section in the tubular specimens. The deformation temperatures were 400°C, 500°C and 570°C and the equivalent strain rate was in the range 0,005-0,5 s^{-1}. The specimens were kept at the deformation temperature for 3 minutes before deformation started to minimize temperature gradients in the specimen and to dissolve any possible precipitates.

Temperature measurements were carried out at several positions on separate specimens to reveal any temperature gradients. The positions are shown in Figure 1a and b.

4. RESULTS AND DISCUSSION

Thermal gradients in the material have three different origins, namely inhomogenities in the induction field, heat flow from the gage section to the head of the specimen and deformation induced heat.

Because the temperature was controlled at different positions in the two geomtries, several temperature measurements were carried out to establish the temperature distribution in non-deformed state. As illustrated in Figure 2a, thermal gradients exist in the axial direction. These gradients increase slightly with increasing temperature and are at the same level for both types of specimens. The surface temperature in the center of the gage region, i.e. the maximum temperature in the deformation zone, is referred to as the deformation temperature, T_{def}. The following relationships between T_{def} and control temperature, $T_{control}$ were found and used to set the control temperature:

$$T_{control}^{solid} = 0{,}984T_{def} + 2{,}69 \quad (8)$$

$$T_{control}^{tube} = 0{,}978T_{def} + 0{,}16 \quad (9)$$

No attempts were made to measure gradients in the radial direction. The effect of heat generation during deformation is discussed below. It appears that the gradients is to low to seriously influence the flow behaviour of the material during deformation. Several experiments were run in which points initially along a straight line on the specimen surface moved during deformation. The

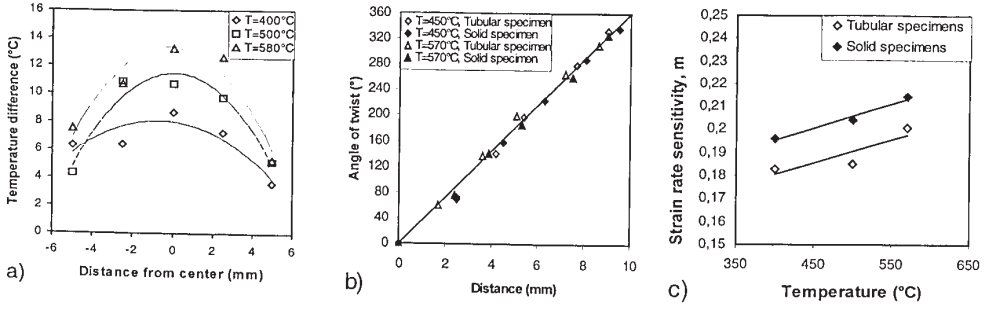

Figure 2 a) Temperature-differences (T_{def} -$T_{control}$) versus position showing the thermal gradients at different temperatures. b) Twist angle after deformation of different points on an initially straight line versus longitudinally position in the gage section. The equivalent strain rate was 0,1 s^{-1}. c) Strain rate sensitivity as a function of deformation temperature.

rotation angle of each points were measured and the results demonstrate that the deformation is uniform in the logitudinally direction, see Figure 2b. The equivalent strain rate was 0,1 s^{-1}, and the same results were obtained for both hollow and massive specimens at 450°C and 570°C.

The strain rate sensitivity was calculated as the slope of a ln M-ln ω-plot, see Eq. 7. The calculation was performed at constant strain and temperature by use of the least square method. The torque-values at the steady state conditions have been used in all evaluations in this work. The strain rate sensitivity, m, for the solid specimen was found to be 0,196, 0,204 and 0,214 at 400°C, 500°C and 570°C, respectively. The values for the tubular specimen is approximately 7 % lower than that for the massive ones, at all temperatures, Figure 2c. The m-values found from Eq. 7 were used to calculate the whole flow curve (Eq. 5), Figure 3a, and the steady state flow stress has been plotted against the corresponding deformation temperature, Figure 3b. The results show that at a strain rate of 0,005 s^{-1} and 0,04 s^{-1} the tubular specimen has a higher flow stress than the solid one, while at 0,4 s^{-1} the calculated flow stress for the two geometries are in good correspondance. The opposite result is obtained when using the quasi-elastic solution (Eq. 2), where the best fit is at high strain rate. The full plastic solution (Eq. 3) over-estimates the results of the tubular specimens for all strain rates. However, not surprisingly the solution of Eq. 5 lies between the quasi-elastic solution and the full plastic solution in all cases. The lower strain rate sensitivitiy of the tubular specimen is obviously a result of the different stress level at different strain rates giving rise to different slopes on the ln M-ln ω-plot.

For the same reason, the calculated activation energy, Q, for hot deformation was higher for a tubular specimen than for a solid specimen. The value for the tubular specimen was 180 kJ/mole and for the solid specimen it was 160 kJ/mole. The standard deviation was 2,0 kJ/mole and 2,5

kJ/mole, respectively. The Q-values were found as the slope of a $\ln\dot{\varepsilon}$ -1/T-plot at constant stress according to the expression of the Zener-Hollomon-parameter $Z = \dot{\varepsilon}\exp(Q/RT)$. The Z-parameter, was also plotted versus the steady state flow stress in a double-logaritmic diagram, Figure 3c. All data fits to a straight line quite well, but the higher activation energy for tubular specimens moves this line to higher Z-values.

What is the origin of the different activation energies and strain rate sensitivities for the two geometries? The torque may be influenced by strain rate, temperature and global deformation like necking and buckling.

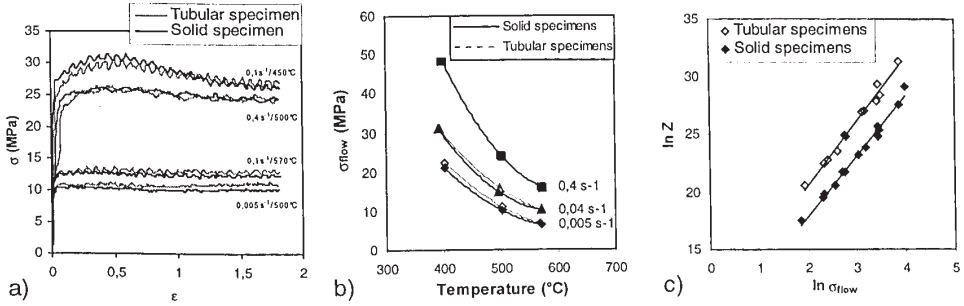

Figure 3 a) Examples of flow curves at different temperatures and strain rates. b) Steady state flow stress (Eq. 6) as a function of deformation temperature at different strain rates. c) The Zener-Hollomon parameter versus steady state flow stress.

The strain rates in the respective tests were similar and had no effect on flow curves.

The measured temperature during deformation was constant in most cases. In a few tests softening were observed, Figure 2a, but the reason for this is unclear. The corresponding temperature-twist curve show a drop in the temperature (≈ 10°C) suddenly after the deformation have started. After reaching a minimum the temperature again increases to the original set value. The temperature-minimum corresponds to the maximum of the flow curve. This change in temperature may explain the observed softening phenomenon.

Another consideration is the generation of heat during deformation. The major part of the deformation work is converted into heat, and the increase in temperature during testing is a function of the amount of heat generated and the amount of heat diffused into the specimen-shoulders. If the deformation rate is low, the heat-generation is the limiting factor and one can assume isothermal conditions. If the deformation rate is high, the heat-diffusion is the limiting factor and adiabatic condition can be assumed. The transition between isothermal and adiabatic condition has been reported to be at an equivalent strain rate of approximately 0,01 s^{-1} [6]. At a temperature of 480°C an increase of 25°C at a strain of 10 radians and a strain rate of 0,3 s^{-1} has been reported in solid specimens of the same geometry as used here [7]. At a strain rate of 3,7 s^{-1} the temperature increase was 35°C [7]. Such results have not been observed in the present work. More heat should be generated in a solid specimen than in a tubular specimen and consequently also a lower flow stress should be measured. This effect should increase with increasing strain rate. However, the contrary seems to be the case, Figure 3a and 3b. It is thus concluded that temperature changes is not the explanation of the differences in the flow stress.

However, the differences can be ascribed to global deformations of the hollow specimens. It is a possibility that the mandrel blocks the flow of the material when buckling of the wall starts to occur, and thus increasing the torque. By visual inspection, all hollow specimens were found to be exposed to such global deformation to a certain extent, and the tendency was increasing buckling with decreasing strain rate. This observations supports the results in Figure 3b. It is thus concluded that the higher flow stress at lower strain rates can be explained by such a distortion of the flow behaviour by the mandrel in the tubular specimens.

5. CONCLUSIONS

1. Thermal gradients of 5-6°C at the surface of the gage section have been observed in both solid and tubular specimens.
2. The thermal gradients do not affect the deformation in the gage section. The deformation seems to be uniformly distributed.
3. The strain rate sensitivity in a solid specimen was found to be 0,196, 0,204 and 0,214 at 400°C, 500°C and 570°C, respectively. The tubular specimens had values that were approximately 7 % lower than that for solid specimens at all temperatures.
4. The activation energy for hot deformation was 180 kJ/mole for tubular specimens and 160 kJ/mole for solid specimens
5. The reason for the different strain rate sensitivity and activation energy is that the flow stress in tubular specimens over-estimates that of the solid specimens at low strain rates. This is most likely due to distortion of the flow behaviour by the mandrel when buckling of the wall in the tubular specimen take place.

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