Original Article

Applicability of shear punch testing to the evaluation of hot tensile deformation parameters and constitutive analyses

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Shear punch testing (SPT) was used to evaluate hot deformation constitutive parameters, and the results were compared with those of the conventional uniaxial tensile testing (UTT) method. Both tests were performed on a rolled Sn–5Sb alloy, as a model material, in the temperature range of 298–400 K and under strain rates in the range of $5 \times 10^{-4}$ to $1 \times 10^{-2}$ s$^{-1}$. Reasonable agreement was found between the parameters obtained in both deformation modes for the power-law, exponential, and hyperbolic sine constitutive equations. The obtained stress exponents and activation energy values in shear deformation were almost the same as those found in the tensile deformation. Therefore, it can be concluded that the data provided by the easy-to-perform SPT can be used for the prediction of constitutive equations as well as deformation mechanisms of the material in the tensile deformation mode. Based on the power-law stress exponents in the range of 4.5–7.0 and activation energy values of about 54–59 kJ mol$^{-1}$, dislocation climb mechanism controlled by the lattice diffusion could be suggested as the main controlling mechanism of the deformation of the alloy in both deformation modes.

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1. Introduction

Obtaining mechanical properties of materials from small samples by using miniature testing techniques seems quite attractive, especially for scarce, valuable and difficult-to-process materials [1]. Among different miniature testing methods, shear punch testing (SPT) has attracted much interest in recent years, due to several advantages including simplicity of the die and punching system, the possibility of using only very small amounts of material, and more importantly, the correlation of the obtained results with those of the conventional uniaxial tensile testing (UTT) method. Shear punch test is based on blanking operation [2], consisting of clamping a small thin sheet sample between die halves and driving a flat cylindrical punch through the sample. By plotting shear stress against normalized displacement, SPT curves that are similar to those obtained in uniaxial tensile tests, are acquired. Mechanical properties such as shear yield stress...
2. Experimental procedure

Rolled Sn–5 wt.% Sb sheets with a nominal thickness of about 1 mm were used in this investigation. The details of the material preparation and processing are explained elsewhere [19]. Tensile specimens were punched from the sheets along the rolling direction. The parallel gage length was 28 mm long and 6.5 mm wide. The specimens were pulled to fracture at the temperatures of 298, 320, 340, 370, and 400 K and at initial strain rates of $5 \times 10^{-4}$, $1 \times 10^{-3}$, $5 \times 10^{-3}$, and $1 \times 10^{-2}$ s$^{-1}$ using an MTS universal tensile testing machine equipped with a three-zone split furnace. Load-extension curves were obtained over the whole gage length, from which the stress at the peak load was calculated as the flow stress needed for the calculation of the hot deformation parameters.

The 1-mm thick slices of the sheets were ground to a thickness of about 0.8 mm, from which disks of 15 mm in diameter were punched for the SPT. A shear punch fixture with a 3.175 mm diameter flat cylindrical punch and 3.225 mm diameter receiving-hole was used (Fig. 1). After locating the specimen in the fixture, the assembly of the specimen and fixture were accommodated by the split furnace. After application of the load, the applied load, $P$, was measured automatically as a function of the punch displacement and the data were acquired by a computer so as to determine

the shear stress of the tested material using the relationship [20]:

$$r = \frac{P}{\pi d t} \quad (1)$$

where $t$ is the specimen thickness and $d$ is the average of the punch and die diameters.

The tensile and shear strain rates, $\dot{i}$ and $\dot{j}$, respectively, are related to cross head speed, $v$, by the following equations:

$$\dot{i} = \frac{v}{l_0} \quad (2)$$

$$\dot{j} = \frac{v}{2w} \quad (3)$$

where $l_0$ is the initial gage length of the tensile samples and $w$ is the clearance between die and punch in the SPT fixture [3]. All SPT tests were performed at the same temperatures and strain rates employed in the tensile tests. This excludes any possibility of strain rate and temperature effects on the level of flow curves. Both tensile samples and the SPT fixture were held for 20 min in furnace to establish thermal equilibrium in the testing arrangement before the test was started.

3. Results and discussion

3.1. Tensile and shear deformation behavior

The tensile and SPT curves of the alloy, obtained at 298 K and under strain rates in the range of $5 \times 10^{-4}$ to $1 \times 10^{-2}$ s$^{-1}$, are shown in Fig. 2. Similar curves were obtained at the other test temperatures of 320, 340, 370 and 400 K. As can be seen in Fig. 2, the strength of the material shows a great dependency on the strain rate in both tensile and shear punch tests, where the peak stress values increase with increasing the applied strain rate, demonstrating a positive sensitivity to strain rate. Furthermore, it is clear that at a given strain rate and temperature, the strength of the material in tensile deformation is greater than the corresponding shear strength. There are different types of constitutive equations for describing the relation between strain rate, flow stress and the temperature.
of deformation, which would be studied in details in the following section.

3.2. Constitutive analysis

In the hot deformation studies, it is important to find appropriate constitutive equations for correlating the flow stress of materials with the strain rate at different test temperatures. Such equations can be used for predicting flow stress of the material at different strain rates or vice versa, for determining the appropriate strain rate for deformation of the material to achieve a specific flow stress level. Whenever, the strain rate and temperature of deformation are both in appropriate ranges, the constitutive equations are valid. In this regard, the relationship between strain rate, flow stress (σ) and temperature (T) can be described by the power-law, exponential and hyperbolic sine functions:

\[ \dot{\varepsilon} = A_1 \sigma^{n_1} \exp \left( -\frac{Q_1}{RT} \right) \] (4)

\[ \dot{\varepsilon} = A_2 \exp (\beta \sigma) \exp \left( -\frac{Q_2}{RT} \right) \] (5)

\[ \dot{\varepsilon} = A_3 [\sinh (\alpha \sigma)]^{n_3} \exp \left( -\frac{Q_3}{RT} \right) \] (6)

where \( A_1, A_2, A_3, n_1, n_2, n_3, \alpha, \beta, \) and \( \dot{\varepsilon} \) are constants, \( Q_1, Q_2 \) and \( Q_3 \) are the activation energy values, and \( R \) is the universal gas constant. At low stresses \( \sigma < 0.8 \), the hyperbolic sine equation, Eq. (6), can be approximated to a power relation (Eq. (4)), while at high stresses \( \sigma > 1.2 \), it reduces to an exponential relation (Eq. (5)). Accordingly, at low stresses, \( n_3 \approx n_1 \), while at high stresses \( \alpha \approx \frac{\beta}{n_1} \). In hot deformation studies, the common procedure is to estimate the \( \alpha \)-value as \( \alpha \approx \frac{\beta}{n_1} \), and this approximation is used in the present study.

The constitutive equations described above can be simply modified for evaluating hot shear deformation behavior in the SPT method by replacing \( \dot{\varepsilon} \) with \( \dot{\gamma} \) and \( \sigma \) with \( r \), as described in our previous publications [17]. This conversion can be carried out using the von Mises criterion for a state of pure shear of kinematically hardening materials, which presents \( \sigma = \sqrt{3} r \) and \( \epsilon = (1/\sqrt{3}) \dot{\gamma} \). Hence, the modified constitutive equations for the hot shear deformation analysis can be rewritten as

\[ \dot{\gamma} = A_1' r^{n_1'} \exp \left( -\frac{Q_1}{RT} \right) \] (7)

\[ \dot{\gamma} = A_2' \exp (\beta' r) \exp \left( -\frac{Q_2}{RT} \right) \] (8)

\[ \dot{\gamma} = A_3' [\sinh (\alpha' r)]^{n_3'} \exp \left( -\frac{Q_3}{RT} \right) \] (9)

where \( A_1', n_1', A_2', \beta', A_3', n_3' \) and \( \alpha' \) are constants. Also, \( Q_1', Q_2' \) and \( Q_3' \) are activation energies found in the shear deformation. Similar to the \( \alpha \) constant, the \( \alpha' \) constant can be approximated as \( \alpha' \approx \frac{\beta'}{n_1'} \).

Due to the constancy of activation energy at a given temperature, the values of \( n_1, n_1', \beta, \beta', n_3 \) and \( n_3' \) parameters can be obtained from the following equations:

\[ n_1 = \left[ \frac{\dot{\varepsilon} \ln (\dot{\varepsilon})}{\sigma \ln (\sigma)} \right]_T \] (10)

\[ n_1' = \left[ \frac{\dot{\gamma} \ln (\dot{\gamma})}{r \ln (r)} \right]_T \] (11)

\[ \beta = \left[ \frac{\dot{\varepsilon} \ln (\dot{\varepsilon})}{\sigma \ln (\sigma)} \right]_T \] (12)

\[ \beta' = \left[ \frac{\dot{\gamma} \ln (\dot{\gamma})}{r \ln (r)} \right]_T \] (13)

\[ n_3 = \left[ \frac{\dot{\varepsilon} \ln (\dot{\varepsilon})}{\sigma \ln \left( \sinh [\alpha \sigma] \right)} \right]_T \] (14)

\[ n_3' = \left[ \frac{\dot{\gamma} \ln (\dot{\gamma})}{r \ln \left( \sinh [\alpha' r] \right)} \right]_T \] (15)

Also, at constant strain rates, the activation energy values of the hyperbolic sine function, \( Q_3 \) and \( Q_3' \), can be obtained from the following equations:

\[ Q_3 = n_3 R \left[ \frac{\dot{\varepsilon} \ln \left( \sinh [\alpha \sigma] \right)}{\dot{\varepsilon} \left( 1/T \right)} \right]_T \] (16)
The relationships between strain rate, peak stress and temperature are shown in Figs. 3 and 4 for the tensile and shear punch tests, respectively. Parameters of the hyperbolic sine constitutive equations (Eqs. (6) and (9)) can be calculated from such plots according to Eqs. (10)–(17), and then, it would be very interesting to compare the obtained parameters for the tensile and shear punch tests. As can be inferred from Figs. 3a and 4a, the power-law stress exponent values can be calculated at each temperature by plotting the strain rate against stress on a log-log scale. The stress exponents were in the ranges of 4.6–7.0 and 4.5–7.0 in tensile and shear punch tests, respectively. It can be observed that the obtained stress exponents in tensile test ($n_1$) and SPT ($n_1'$) are very close to each other at different test temperatures. This similarity between the power-law stress exponents found in the tensile and shear punch tests seems reasonable by assuming the linear relation between $\sigma$ and $\dot{\varepsilon}$ ($\sigma = K\dot{\varepsilon}$, where $K$ is a constant) and also, considering the fact that similar strain rates have been used in both tests. Although the value of constant $K$ does not affect the power-law stress exponent values, it should be noted that this constant is usually around 1.77, when comparing the yield stresses, and around 1.80, when comparing the peak stresses [3]. However, plotting the obtained UTS values against the USS values in Fig. 5 demonstrates that the K constant is 2.12 in the present study. The K constant greater than the theoretical von Mises ratio of 1.73 is believed to be caused by friction, bending, and stretching of the materials in the deformation zone of the SPT [21]. These effects may be intensified at high temperatures, while all previous studies [3,9–11] on the relationship between tensile and shear punch tests have been carried out at room temperature.

The $\beta$ and $\beta'$ constants in Eqs. (12) and (13) can be calculated by plotting the strain rate versus stress on a semi-logarithmic scale, as shown in Figs. 3b and 4b, respectively. Again, considering the linear relationship between $\sigma$ and $\dot{\varepsilon}$, it is anticipated that the $\beta'$ constant is equal to $K\dot{\varepsilon}$, which seems to be almost true when comparing the $\beta$ and $\beta'$ constants at different test temperatures. The ratio of the average $\beta$ value to average $\beta'$ is about 2.3, which is almost comparable with the 2.12 value found for the K constant in Fig. 5.

After calculation of the $n_1$ and $\beta$ constants at all test temperatures, the average $\alpha$ constant was calculated to be around 0.031 according to the $\alpha = \beta/n_1$ relation. As discussed above and was also shown in Figs. 3a and 4a, the obtained $n_1$ values in tensile test are almost equal to $n_1'$ values found in the SPT. Accordingly, it is expected that the $\alpha'$ constant in the SPT is equal to $K\dot{\varepsilon}$, considering the relationship between $\beta$ and $\beta'$ constants. Such approximation seems to be valid according to the calculated average $\alpha'$ constant which is about 0.071. Therefore, according to the linear relationship between stresses in tensile and shear deformations, it can be concluded that the $n_1$, $\beta$ and $\alpha$ constants in the tensile constitutive equations can be estimated form the corresponding $n_1'$, $\beta'$ and $\alpha'$ values in the SPT, where $n_1 = n_1'$, $\beta = \beta'/K$ and $\alpha = \alpha'/K$.

The variations of the strain rate with sinh ($\omega\dot{\varepsilon}$) and sinh ($\omega'\dot{\varepsilon}$) plotted on log-log scales are shown in Figs. 3c and 4c. It can be observed that the $n_3$ and $n_3'$ constants are in the ranges

$$Q_{\dot{\varepsilon}} = n_2 R \left[ \frac{\partial \ln [\sinh (\omega')]}{\partial (1/T)} \right]_{\dot{\varepsilon}}$$

(17)
of 3.9–4.5 and 4.0–4.5, respectively. Average \( n_3 \) and \( n'_3 \) values of about 4.26 and 4.23 were respectively, used for the calculation of the \( Q_3 \) and \( Q'_3 \) activation energies according to Eqs. (16) and (17). The variations of sinh \((\omega\sigma)\) and sinh \((\omega'\tau)\) with the reciprocal of temperature are plotted on a semi-log scale and at constant strain rates in Figs. 3d and 4d, respectively. As can be observed, average activation energy value of about 54.0 kJ mol\(^{-1}\) has been obtained in the tensile test (Fig. 3d), which is almost close to the activation energy value of 58.9 kJ mol\(^{-1}\) calculated for the SPT method (Fig. 4d).

The \( A_2 \) and \( A'_3 \) constants in Eqs. (6) and (9) can be obtained by plotting \( i \exp(Q/RT) \) and \( \dot{\gamma} \exp(Q'/RT) \) against sinh \((\omega\sigma)\) and sinh \((\omega'\tau)\) on log-log scales, respectively. Such plots are shown in Fig. 6 for comparison and also for the validation of linear relationships between the supposed parameters. An average activation energy value of 56.4 kJ mol\(^{-1}\) was assumed in both testing conditions. It can be observed that all data points obtained at different test temperatures can be fitted to single lines in both tests:

\[
i \exp \left( \frac{54,600}{RT} \right) = 346,279 \times \text{sinh}(0.031\sigma)^{6.3}
\]

(18)

\[
\dot{\gamma} \exp \left( \frac{54,600}{RT} \right) = 373,248 \times \text{sinh}(0.071\tau)^{4.1}
\]

(19)

According to these equations, \( A'_3/A_2 \approx 1.07 \), which is almost close to 1. This value seems reasonable, since at equal strain rates and activation energies:

\[
\frac{A'_3}{A_2} = \frac{\text{sinh}(\omega\sigma)^{3.5}}{\text{sinh}(\omega'\tau)^{3.5}} \approx 1
\]

(20)

which should be around 1, since \( n_3 \approx n'_3 \) and \( \omega\sigma \approx \omega'\tau \). It should be noted here that the \( A_2 \) and \( A'_3 \) constants can be considered as material dependent constants, similar to the \( A_1 \) constant in the power-law equation (Eq. (4)), which depends on material properties such as stacking fault energy [22,23]. However, this material dependency would not affect the relation between the \( A_2 \) and \( A'_3 \) constants (Eq. (17)), since here the same material has been used in both tests.

According to the obtained results, it is concluded, therefore, that the constitutive hyperbolic sine equation found in the SPT can be used for the prediction of the corresponding
Due to the similarity of the constitutive parameters found in the tensile and shear punch tests, the deformation mechanisms can also be identified from these constitutive parameters. In this regard, and under the experimental conditions where the power-law creep relation is valid, different mechanisms have been proposed for various combinations of stress exponents and activation energies. Additionally, there is a substantial contiguity between creep and hot working, so that the controlling deformation mechanism could be essentially similar [26]. According to the theories of dislocation climb-controlled creep, the stress exponent has the value in the range 4–6 and the activation energy has the value of the activation energy of lattice self-diffusion [27]. Therefore, the power-law stress exponents, \( n_1 \) and \( n'_1 \), which were found to be, respectively, in the ranges of 4.6–7.0 and 4.5–7.0 (Figs. 3a and 4a), and the activation energy of about 54–59 kJ mol\(^{-1} \), which is very close to the estimated activation energy for lattice diffusion in Sn (60.3 kJ mol\(^{-1} \)) [28], suggest that dislocation climb controlled by lattice diffusion could be the dominant deformation mechanism in the studied alloy in the temperature range of 298–400 K. The obtained power-law stress exponents and activation energies found in this study are comparable to those reported previously for the Sn–Sb alloy obtained by different methods. Power-law stress exponents in the range of 3.4–7.1 and activation energy of 55 kJ mol\(^{-1} \) have been reported for a wrought Sn–Sb alloy [19]. Accordingly, due to the similarity of the power-law stress exponents and activation energy values found in tensile and shear punch tests, the constitutive parameters found in the SPT can also be used for the identification of deformation mechanism of the material in the investigated ranges of temperature and strain rate.

4. Conclusions

The correspondence between hot deformation behaviors under uniaxial and shear modes was assessed for a Sn–Sb alloy. This was achieved by the shear punch testing, as a localized testing technique, and the results were compared with those obtained by the conventional tensile testing technique. The following conclusions were made:

- Constitutive parameters calculated from the SPT data can be simply converted to the corresponding parameters in the tensile deformation mode.
- While the power-law and hyperbolic sine stress exponents are almost identical in both deformation modes, the \( \beta \) and \( \alpha \) constants in the exponential and hyperbolic sine equations are proportional to the corresponding values in the SPT. The calculated activation energy values were also found to be close to each other in the tensile and shear deformation modes.
- Due to the similarity of the power-law stress exponents and activation energy values, obtained in both deformation modes, dislocation climb mechanism controlled by the lattice diffusion was suggested as the main controlling mechanism of the deformation in both cases, showing the capability of SPT for the identification of hot deformation mechanisms.
Conflicts of interest

The authors declare no conflicts of interest.

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