Hardness–stress–strain correlation in aluminium—A simpler alternative to viscoplasticity in metal forming

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MS received 11 September 1995; revised 3 February 1996

Abstract. Local stress and strain variations in the deformation zone can be ascertained by measuring hardness. Hardness is correlated with strain and stress. The expressions discussed later are useful in determining the local variations in stress and strain from hardness measurement. It is a simple method compared to viscoplasticity. One can estimate the forces required for a forming process. It helps in the choice of equipment, design of tooling and selection of lubricant for the particular process.

Keywords. Stress; strain; hardness; power law; log-log plot.

1. Introduction

Aluminium and its alloys are classified into cast and wrought alloys. One can presume from this that mechanical processing of aluminium is important. Extrusion is used to produce rods, tubes and sections, rolling to produce sheets, wire drawing to produce wires, tube drawing to produce long tubes and sheet metal working to produce utensils and other shapes. All these processes involve heterogeneous deformation and thus variations in stress and strain occur locally, in the deformation zone during processing. Average forces for the overall process will be influenced by these local variations. Estimating such forces accurately will help in choosing machines of sufficient capacity, designing of dies and selecting lubricants to minimize friction. Viscoplasticity (Laue and Stenger 1981; Avitzur 1983; Lange 1985) is one way of achieving this. It is a complex and time consuming method. A simpler alternative is suggested to ascertain local stresses and strains by measuring hardness in the deformation zone systematically. Already hardness and stress relationship have been reported (Tabor 1951; Lange 1985) and hardness and strain relationship (in mild steel) have been reported (Dharmaveera and Srinivasan 1995). The present work is a further step in this direction.

2. Experimental

Commercially pure aluminium has been chosen for the present study as it is a widely used engineering material with many applications. Rods of 25 mm diameter have been taken and annealed at 350°C for 2 h to remove residual stresses. These rods were machined into samples of height 37.5 mm and diameter 25 mm with a height to diameter ratio of 1.5. Above this ratio buckling will interfere with the test.

Simple compression testing has been done on 3 samples in an UTM of 100T capacity and force-stroke diagrams are generated. Several samples were upset to different heights in the same machine to get different strains. These samples were cut up vertically into two and at the centre of each half several hardness measurements were done and the average for each sample taken apart from the maximum and minimum

Figure 1. True stress against true strain for aluminium.

values to ascertain the scatter band. Thus for each strain there will be an average hardness value and one maximum and one minimum hardness value.

3. Results

From the force-stroke diagram true stress and true strain are calculated and plotted as shown in figure 1. Log-log plot of true stress and true strain has been shown in figure 2. A linear line is obtained whose slope gives the strain hardening exponent. The strength coefficient is equal to the value of stress when strain is equal to 1.0. The flow equation is $\sigma = k\epsilon^n$ and $\ln \sigma = \ln k + n \ln \epsilon$, where, k is strength coefficient and n the strain hardness exponent. In the present case $k = 260$ and $n = 0.23$. Maximum and minimum hardness values are plotted against true strain in figure 3. As strain increases the scatter band

Figure 2. Log-log plot of true stress against true strain.

Figure 3. Maximum and minimum hardness against true strain.

widens. Average hardness and true stress are plotted against true strain in figure 4. From this one can conclude that $\sigma = 3.1 H$ (BHN) in the plastic region.

Log-log plot of hardness and true strain is shown in figure 5. A power law relation is valid for the two [i.e. $H = C\epsilon^h$, $\ln H = \ln C + h \ln \epsilon$]. For aluminium the values are found to be $C = 100$ (hardness coefficient) and $h = 0.37$ (hardness exponent).

Figure 4. Plot of true stress and average hardness against true strain.

Figure 5. Log-log plot of average hardness against true strain.

4. Discussion

Commercially pure aluminium has a FCC crystal structure with twelve slip systems and a low CRSS (1.02 MPa). Von Mises criterion of five independent slip systems for ductility is also satisfied in aluminium. It is soft and accepts heavy deformation

($\varepsilon = 0.74$). Work hardening is not that rapid. Aluminium has a high stacking fault energy (200 mJ/m^2). Cross slip is easier. Dynamic recovery takes place in aluminium. It leads to annihilation of pairs of dislocations during straining. It makes the material capable of undergoing more deformation at lower stress. Flow curve is one order of magnitude lower than in cold working. Power Law expression is valid for (i) stress and strain and (ii) hardness and strain. A linear relationship is valid for hardness and stress. The significance of $\Delta\sigma/\Delta\varepsilon$ in a compression test is to be ascertained. It has a clear cut role in tension. When $\Delta\sigma/\Delta\varepsilon = \sigma$ instability starts in tension. In compression no such thing has been reported. In tension Hart equations of stability are valid if strain rate is taken into account. In compression also such equations exist but the inequalities associated with stable and unstable flow are reversed.

$$\left. \begin{array}{l} (\gamma + m) \leq 1 \quad \text{stable flow} \\ (\gamma + m) \geq 1 \quad \text{unstable flow} \end{array} \right| \text{in compression}$$

where,

$$\gamma = \frac{1}{\sigma} \frac{\Delta\sigma}{\Delta\varepsilon} \bigg|_{\dot{\varepsilon}, T},$$

$$m = \frac{\Delta \ln \sigma}{\Delta \ln \dot{\varepsilon}} \bigg|_{\varepsilon, T},$$

$$\alpha = \frac{\gamma - 1}{m}.$$

The value of α will determine whether shear band formation is prevalent or not. The role played by $\Delta\sigma/\Delta\varepsilon$ in compression is to be explored further. For a perfectly elastic solid $n = 0$ and for a perfectly plastic solid $n = 0.5$ and for most metals n lies between the two (Dieter and Bacon 1988). In the present case $n = 0.23$, which is well within the limits.

5. Conclusions

The following relationships are valid for commercially pure aluminium.

$$\sigma = 260 \varepsilon^{0.23},$$

$$H = 100 \varepsilon^{0.97},$$

$$\alpha = 3.1 H(\text{BHN}).$$

Similar relationships can be established for other metals and alloys. Once this is done it is easy to estimate local stress and strain variations from point to point in the deformation zone by measuring hardness at every point and using the above relationships.

References

- Avitzur B 1983 *Handbook of metal forming processes* (New York: John Wiley) p. 71
- Dharmaveera N and Srinivasan K 1995 *Tool & Alloy Steels* **29** 63
- Dieter G E and Bacon D 1988 *Mechanical metallurgy* (London: McGraw Hill) p. 287
- Lange K 1985 *Handbook of metal forming* (New York: McGraw Hill) pp 28–29 and pp 34–35
- Laue K and Stenger H 1981 *Extrusion* (Ohio: ASM) p. 60
- Tabor D 1951 *J. Int. Met.* **79** 1