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Deformation field variations in equal channel angular extrusion due to back pressure

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Flow lines were analysed in aluminium alloy 6061 during equal channel angular extrusion (ECAE) in a 90° die with and without the application of back pressure during pressing. The lines appeared much more rounded when a back pressure was applied compared to the case of conventional ECAE testing. With the help of an analytic flow function, the deformation field was obtained. It is shown that back pressure slightly lowers the total strain, strongly increases the size of the plastic zone and significantly reduces the plastic strain rate.

Keywords: ECAE; Flow lines; Back pressure; Plastic deformation

Since the invention of the equal channel angular extrusion (ECAE) test by Segal in 1974 [1], four types of approaches have been proposed to describe the deformation field during this special extrusion test. The first one, which originates from Segal himself, is called the simple shear model [2] and applies in the intersection plane of the two channels. The second calls for the experimental flow lines from which the deformation gradient is calculated, and then the strain field is obtained in a completely experimental way [3]. The third one is the so-called fan model, proposed by Beyerlein and Tome [4], where the plastic zone has a fan-like form and the flow lines are circular within the fan. It predicts a constant von Mises equivalent strain rate within the fan along a flow line which depends inversely on the distance from the inner corner of the die. Finally, the fourth model approaches the whole flow line with a relatively simple analytic function from which the velocity field and all components of the strain rate tensor can be readily obtained [5].

The problem with the simple shear model is that the deformation is assumed to take place in a very narrow zone with an unknown (theoretically infinite) strain rate, while it has been shown experimentally [3], as well as by finite element calculations [6,7], that the strain zone can be relatively large and the strain rate is limited. The disadvantage of the second model—which uses only the experimental flow lines—is that it cannot describe the deformation field in a continuous way. Finally, the fan model—although it can lead to satisfactory texture predictions [4]—still retains a discontinuity in the deformation field at the entry and the exit points of the plastic zone (as in the simple shear model).

In the present work, following the works presented earlier [5,8], the entire flow field is described by an analytic function that was recently generalized to any die angle including possible asymmetry of the flow line:

$$f(x,y) = \frac{1}{m}(y\sin\Phi - x\cos\Phi)^n + (y\sin\alpha + x\cos\alpha)^n = (y_0\sin\alpha + x_0\cos\alpha)^n. \quad (1)$$

Here Φ is the angle of the die (90° in the present work), n is the so-called shape parameter, m accounts for deviations in the entry and exit positions of the lines, and finally the α angle expresses the asymmetry in the shape. x and y are the coordinates along the flow line measured from the inner corner position, while x_0 and y_0 are the initial positions before deformation begins (see Fig. 1b for the coordinate system). An incompressible velocity field is defined from Eq. (1) as follows:

$$v_x = \lambda\frac{\partial f}{\partial y} = -v_0\frac{\sin\alpha p^{n-1} + \frac{\sin\phi}{m}q^{n-1}}{c^{n-1}}, \quad (2)$$

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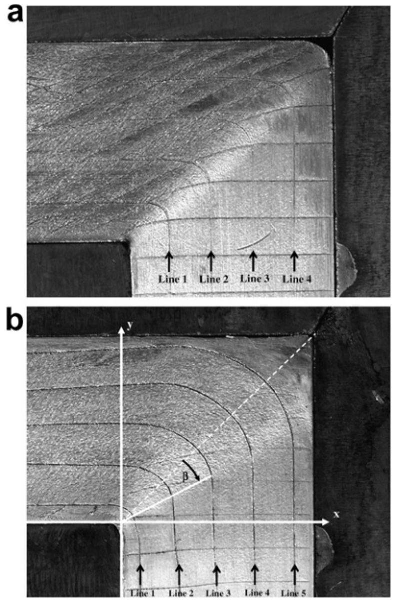

Figure 1. Macro-photo of the deformed Al6061 samples showing the flow lines in their middle sections: (a) without back pressure (WBP); (b) with back pressure (BP).

$$v_y = -\lambda \frac{\partial f}{\partial y} = v_0 \frac{\cos \alpha p^{n-1} - \frac{\cos \phi}{m} q^{n-1}}{c^{n-1}}, \quad (3)$$

where the c, p and q parameters are given by

$$c = (y_0 \sin \alpha + x_0 \cos \alpha), \quad p = (y \sin \alpha + x \sin \alpha),$$
$$q = (y \sin \phi - x \cos \phi).$$

The λ parameter is obtained from the velocity v_0 at the entry position:

$$\lambda = -\frac{v_0}{nc^{n-1}}. \quad (4)$$

By further partial derivation of the velocity field, all the components of the plastic velocity gradient $\boldsymbol{L}$ are obtained:

$$L_{xx} = -v_0(n-1)\left[c^{1-n}\left(p^{n-2}\sin\alpha\cos\alpha - q^{n-2}\frac{\sin\phi\cos\phi}{m}\right) - c^{1-2n}\left(p^{n-1}\sin\alpha + q^{n-1}\frac{\sin\phi}{m}\right) \times \left(p^{n-1}\cos\alpha + q^{n-1}\frac{\cos\phi}{m}\right)\right],$$

$$L_{xy} = -v_0(n-1)\left[c^{1-n}\left(p^{n-2}\sin^2\alpha - q^{n-2}\frac{\sin^2\phi}{m}\right) - c^{1-2n}\left(p^{n-1}\sin\alpha + q^{n-1}\frac{\sin\phi}{m}\right)^2\right],$$

$$L_{yx} = v_0(n-1)\left[c^{1-n}\left(p^{n-2}\cos^2\alpha + q^{n-2}\frac{\cos^2\phi}{m}\right) - c^{1-2n}\left(p^{n-1}\cos\alpha - q^{n-1}\frac{\cos\phi}{m}\right)^2\right],$$

$$L_{xx} = -L_{yy}, L_{xz} = L_{zx} = L_{zy} = L_{yz} = L_{zz} = 0. \quad (5)$$

The symmetric part of the above velocity gradient defines the strain rate tensor from which the von Mises equivalent strain rate can be obtained. An integration of the latter along the flow line gives the total von Mises strain in one pass. The three parameters of the flow line (n, m and α) can be readily identified from experimental flow lines. For more information about the use of a flow line model, see Refs. [5,8,9].

The experiments were carried out at Monash University on aluminium alloy 6061 at room temperature using an ECAE machine with controlled back pressure. This machine provides computer control of the forward and backward pressures and velocity of the forward punch; its features have been described elsewhere [10]. The ECAE with controlled back pressure has many advantages including processing of low-ductility materials [10], and therefore a comparative study of strain field in samples processed with and without back pressure has significant merit. Two samples with a cross-section of $20 \times 20\ \text{mm}^2$ and a length of 100 mm were split up longitudinally along the middle plane, and a grid representing the flow lines and transverse lines was engraved on the internal surface using a diamond stylus. Then two interrupted ECAE tests with a forward punch velocity of $2\ \text{mm s}^{-1}$ have been performed on these samples. The back pressure was preset at two levels: 0 MPa for the first sample and 200 MPa for the second sample. After extracting the samples from the die, the grid was photographed. Figure 1a shows the deformed sample without applying a back pressure (case WBP), while Figure 1b displays the flow lines when a back pressure of 200 MPa was applied during the test (case BP).

As can be seen in Figure 1a and b, the shape of the flow lines changes radically when back pressure is applied; they become much more rounded and a dead-metal zone develops in the outer corner. The engraved flow lines were then fitted with the flow function presented in Eq. (1) above. The quality of the fit can be appreciated in Figure 2. For each line, the parameters are different; the evolution of the n and m parameters as a function of the entry position (x_0) is displayed in Figure 3, while the α values are shown in Table 1. Although the position dependence of the parameters was neglected in the partial derivatives of Eqs. (2)–(5) above, the present approach is a possible modelling of individual flow lines that would correspond to a homogeneous distribution of the parameter values within the plastic strain zone. It is actually possible to take into account the variation of the parameters in the modelling, leading to more general, though more complex, formulas; for more details, see Ref. [9]. Nevertheless, the results obtained with the more general development remain nearly the same.

As can be seen in Figure 2, the asymmetry increases with back pressure. The shape parameter n has much higher values for the BP compared to the WBP case. In both cases, n increases systematically with the flow line position x_0. Similar trends were observed previously in finite element calculations [5] as well as with the help of texture development simulations in the first pass [11]. Concerning the m parameter, it is practically 1.0 in the WBP case while it is significantly smaller with BP. This means that the exit position of the flow line deviates