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The role of back-pressure in equal channel angular extrusion

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Equal Channel Angular Extrusion (ECAE), developed and patented in Russia by Segal in 1977, has become in the last few years a very popular tool for studying the evolution of microstructure and properties under severe plastic deformation. It is believed that the strain-stress characteristics are uniform in a cross-section of the billet and this uniformity of the stress-strain distribution ensures the uniformity of microstructure and mechanical properties in ECAE processed billet. However, some experimental data such as the fracture of the extruded billet, which is initiated at the inner surface of the sample, has caused doubts about uniformity of stress-strain distribution. This non-uniformity has been proved recently by Finite Element Simulation.

This paper reviewed our results from over six years of work using a unique machine for ECAE with computer controlled back-pressure and velocity of the backward punch. Theoretically back-pressure has been introduced in the earlier papers of Segal. However, practically back-pressure has not been widely used or often used in a primitive form of the consequent extruded sample and its role has not been understood.

1. Introduction

Equal Channel Angular Extrusion (ECAE), developed and patented in Russia by Segal in 1977 [1], has become in the last few years a very popular tool for studying the evolution of microstructure and properties under severe plastic deformation (SPD). The process is the extrusion of a well-lubricated billet through a die with two channels of equal cross-section intersecting at an angle. In ECAE, it is believed, that deformation is localized in the small area around the channels' meeting line and as result a large uniform simple shear strain is imposed in the billet [2, 3]. It is also believed that the stress characteristics are uniform in the cross-section of the billet and that this uniformity of the stress-strain distribution ensures the uniformity of microstructure and mechanical properties in ECAE processed billet.

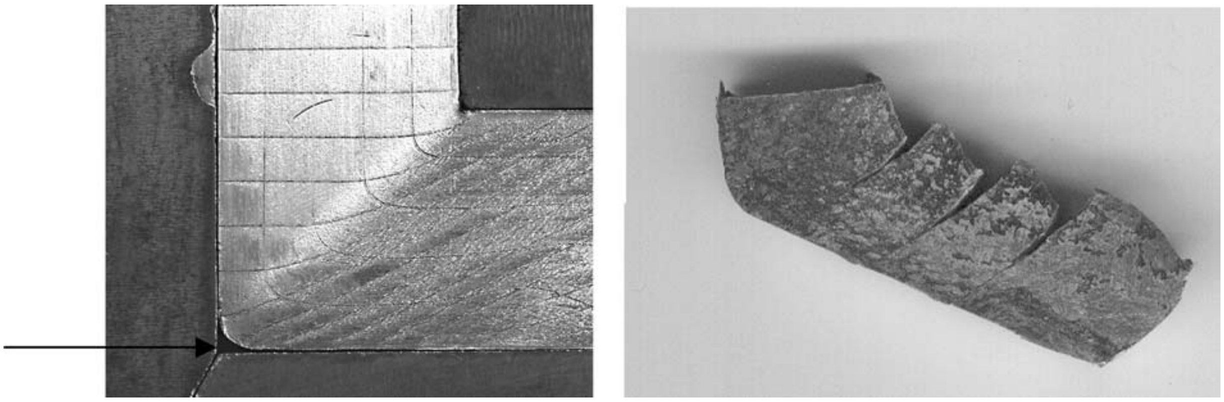
Even though, Segal suggested in his more recent paper [4] that change in friction and tool design leads to the change of deformation mode from a simple shear to a more complicated and non-uniform strain state, this fact has been ignored by the majority of scientific community. Only very few research groups around the world performed ECAE with applied back-pressure [5, 6]. A gap appearing between specimen and corner of the die, Fig. 1a, especially for strain-hardening material and the fan-shape deformation zone were commonly considered negligible. Only recently, some numerical simulations and experimental investigation using grid specimens were performed to understand the importance of back-pressure for improvement of strain pattern [7, 8].

Non-uniformity of stress-strain distribution has also been proven by fracture of extruded samples, that failed in a very particular manner shown in Fig. 1b with the cracking initiated at the surface of the specimen being in contact with the internal surface of the die. Only a few papers have been published on the studies of fracture during ECAE [9, 10]. In these papers Finite Element (FE) simulation has been performed to explain the non-uniform distribution of stress and strain during ECAE. It was shown that the constitutive behaviour of the material and the tool design have a significant effect on the degree of non-uniformity during ECAE [9]. As a measure to improve the deformation uniformity and to prevent failure, the stabilising pre-straining of the specimen prior to ECAE has been suggested [10].

In our opinion, an excellent way to overcome this problem is the application of back-pressure. In this paper the studies of the positive role of the applied back-pressure during ECAE are reviewed and the influence of a back-pressure on the uniformity of the stress-strain distribution and the prevention of fracture is shown.

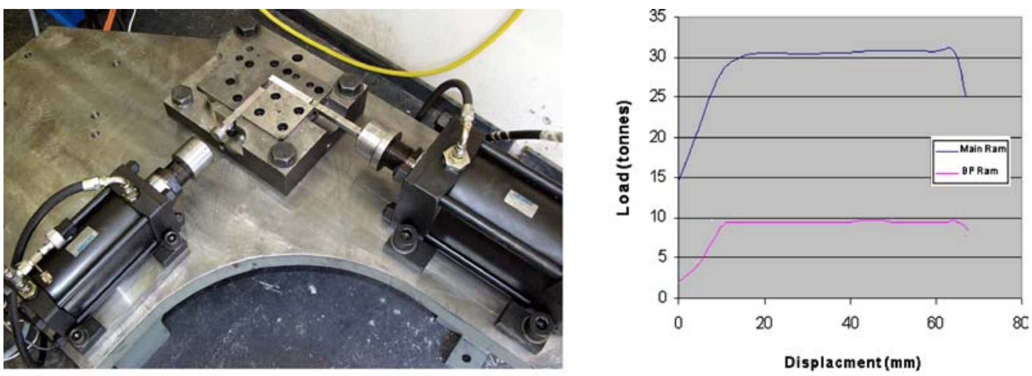
2. ECAE with back-pressure

Theoretically back-pressure was introduced at the initial stage of ECAE development [11]. However, in practice back-pressure was only used by a few research groups [5, 6], or often used in a primitive form of the consequent extruded sample and its role has not been understood. In some investigations the effect of



(a) (b)

Figure 1 Defects which can form during ECAE without back-pressure: (a) the gap forming between the die and the specimen (grid lines show the fan-shaped deformation zone) and (b) fracture of magnesium sample after one pass of ECAE at room temperature through 120° die.



(a) (b)

Figure 2 Equipment and typical loading curves for ECAE with controlled back-pressure: (a) tooling for 90° pressing and (b) forward and back forces versus displacement of punch.

back-pressure was compared to the effect of friction [5]. However, the design of dies with moving bottom wall significantly decreasing friction was claimed to produce a back-pressure. The machine designed and manufactured in Monash University, Fig. 2a, provides computer controlled ECAE with possibility of controlling not only the forward- and with backward-pressures, but also velocities of both punches. That allows to program different schedules for ECAE experiments and keep the back-pressure at a constant pre-set level. The velocity of the extrusion and the forward pressure are also controlled by computer. The ECAE machine has a capacity of 50 tonnes forward force and 25 tonnes of back force. An example of a typical load displacement diagram for ECAE is shown in Fig. 2b.

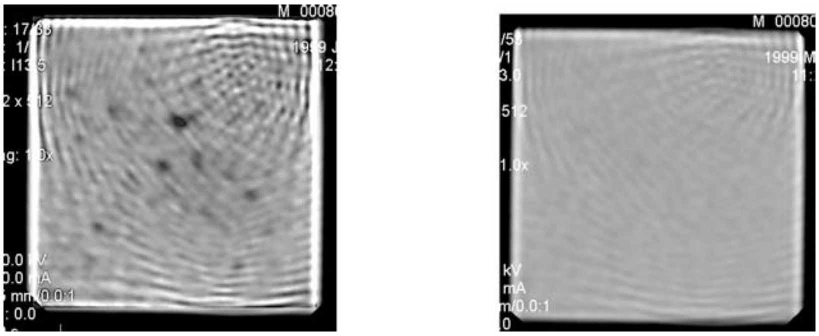
Using this machine, the role of back-pressure and several physical phenomena have been studied. It has been shown that there is no gap between the specimen and the die in the presence of back pressure and that the deformation mode is a simple shear as described theoretically for ideal rigid-plastic material in 117.

2.1. Role of back-pressure in suppressing damage accumulation during ECAE

The development and recovery of damage due to severe plastic deformation and as a function of hydrostatic pressure has been investigated for aluminium alloys [12]. Damage accumulation has been shown to be proportional to the amount of plastic strain, while the intensity of accumulation is dependent on the stress state. It has been shown that the application of back-pressure leads to a suppressing of damage accumulation and closure of defects, while the absence of back-pressure leads to the development of defects due to severe plastic deformation.

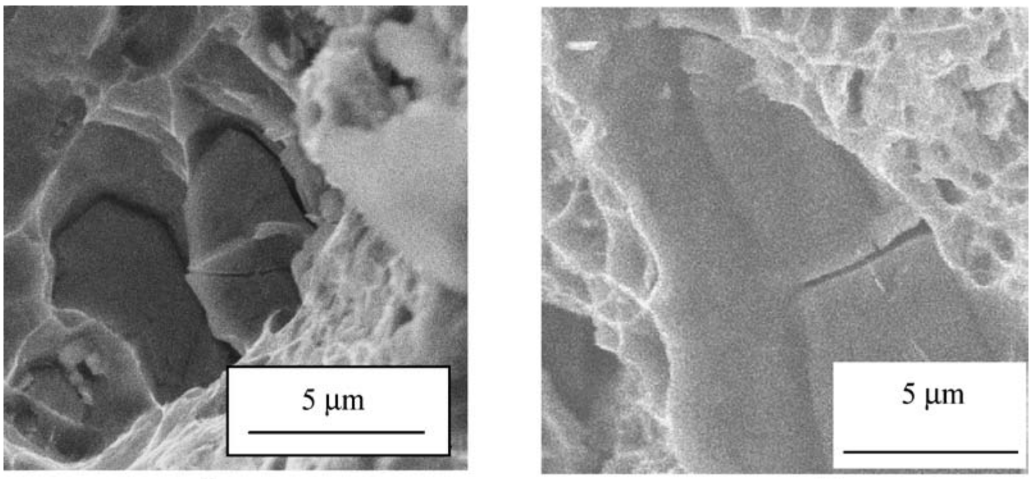
The existence of pores before and after processing was studied using stereo x-radiography as shown in Fig. 3. Three typical cases were observed during X-ray CT scan measurements; (a) an elliptical or spherical pore were transformed to a similar shape after deformation, (b) the defects became invisible after deformation, and (c) the new defects became visible after deformation. The number of closed defects and the number of generated defects were strictly dependent on a level of back-pressure applied during ECAE [13].

In addition, the ability of aluminium alloys to withstand severe plastic deformation under different stress histories characterised by lower bound ductility (LBD) has been studied [14]. It was shown that the fracture of the specimen initiated by cracking at the surface of the specimen which was in contact with the internal surface of the die can be completely suppressed by applied back-pressure.



(a) (b)

Figure 3 X-ray CT image of a sample with generated defects after ECAE: (a) no back pressure and (b) with back-pressure.



(a) (b)

Figure 4 Character of fracture of intermetallic particles in ECAE sample: (a) propagation of microcrack through the particle at low back-pressure and (b) microcrack arrested at high back-pressure.

2.2. Role of back-pressure in grain-refinement and the character of post-deformation fracture

The role of back-pressure in grain-refinement of cast Al-5 wt%Fe alloy by ECAE has been studied in conjunction with Professor V. Stolyarov from The Institute of Physics of Advanced Materials, Ufa State Aviation Technical University, during his visit to Monash University and published in [15].

It has been shown that brittle cast alloy which failed after two ECAE passes in the absence of back-pressure withstands the severe plastic deformation up to 18.4 without failure (16 passes) by applying ECAP with a back-pressure not less than 275 MPa. ECAE of the cast alloy led to strong refinement of structure with a mean grain size (in the aluminium-based matrix) of 325 nm at a high level of back-pressure and a mean grain size of 420 nm at low level of back-pressure.

SEM observations established that the fracture of specimens from the ECAE samples is predominantly ductile. Increasing back-pressure retards cracking in intermetallic particles and promotes enhancement of ductility of the alloy processed by ECAE, because the arrest of cracks in the brittle particles, Fig. 4, decreases the number of nucleation sites of micro cavities formed by a decohesion of hard particles in the matrix.

2.3. Role of back-pressure in densification of magnesium alloy particles using ECAE

The production of solid rod from magnesium alloy particles by ECAE with back-pressure is reported in [16]. It was found that shear deformation with imposed hydrostatic pressure promotes compaction very effectively. Samples compacted at the defined optimal back-pressure, Fig. 5, had almost theoretical density equal to 1.74 g/cm^3 compared with the density of pure magnesium, 1.741 g/cm^3.

3. Change of the stress-strain state during ECAE with back-pressure

The stress-strain distribution during ECAE with different levels of back-pressure has been modeled by FE software “Q-Form” [17] designed specially for modeling forging and extrusion processes. The Q-Form system is based on flow formulation and the material is an incompressible rigid-viscoplastic continuum. The system provides coupled thermo-mechanical interactive simulation of metal flow, where constitutive behaviour is described by the equivalent stress as a function of equivalent strain, strain rate and temperature in analytical or table form. The program predicts the metal flow, distribution of stresses, strains and temperature during the deformation. The simulation is performed

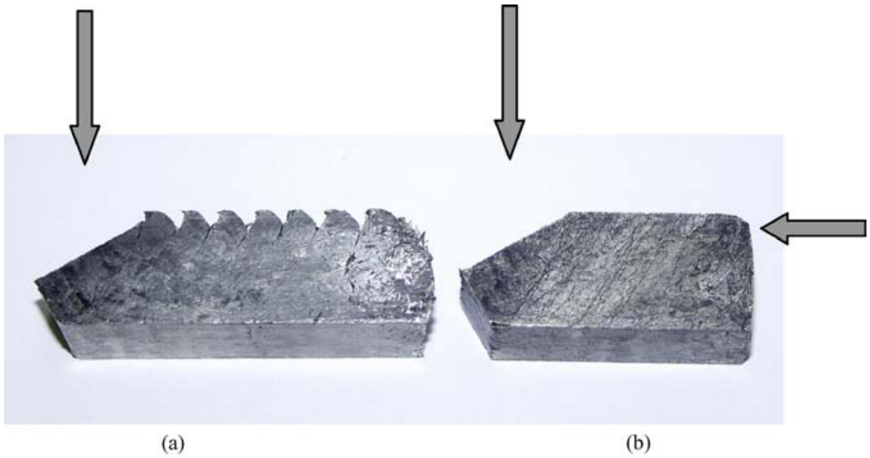


Figure 5 Compacted magnesium alloy particles processed by ECAE with: (a) no back-pressure and (b) 60 MPa back-pressure.

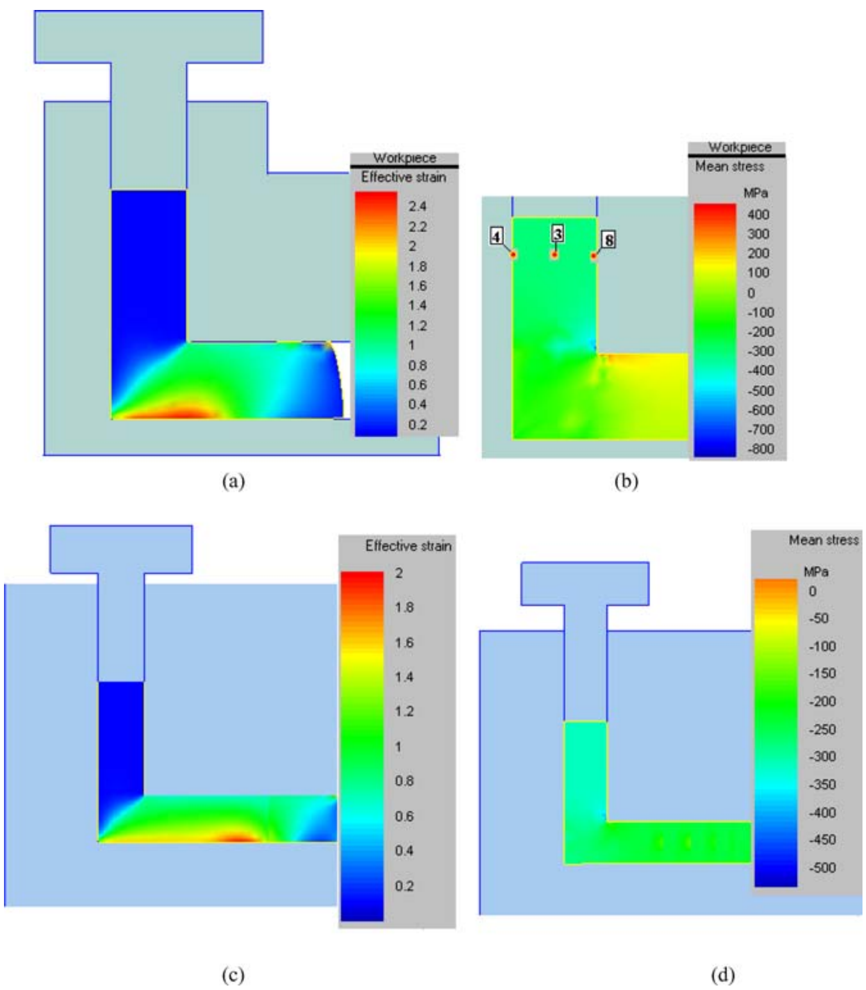


Figure 6 The distribution of stress-strain during ECAE without (a, b) and with back-pressure (c, d). a, c—effective strain; b, d—mean stress.

step-by-step using increments in time and uses the integrated Smart Mesh Generator that provides a completely automatic finite element mesh generation at each time step with a density dependent on strain gradient and surface geometry. Simulation of ECAE was performed at room temperature, uniform friction at the die walls with coefficient of friction of 0.1. The velocity of the forward punch was kept constant during the ECAE equal to 6 mm/s. The distribution of accumulated strain after pass was used as initial field during simulation of the following pass, what is one of the fiture of Q-Form system.

The modeling of ECAE without back-pressure confirmed the non-uniformity of strain-stress distribution. The effective strain and mean stress distribution during ECAE of the specimen from aluminium alloy 2024 are shown in Fig. 6.

The software allows observation of the history of stress and strain variables in any particular particle of the extruded specimen. The mean stress history is

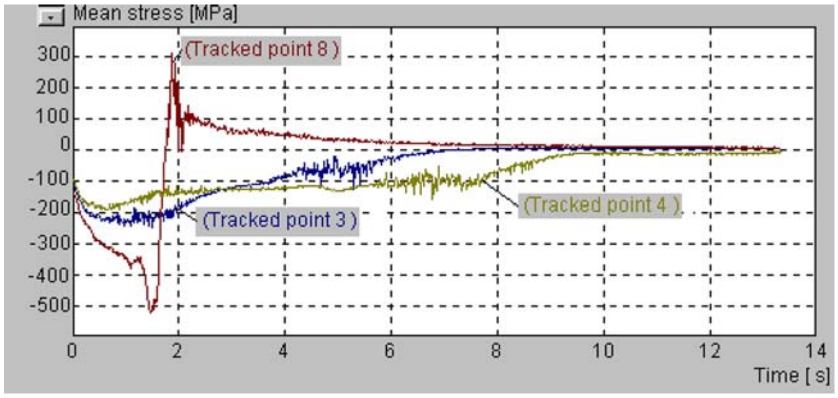


Figure 7 The mean stress history for points at the middle flow line (3) and at the outer (4) and inner (8) surfaces.

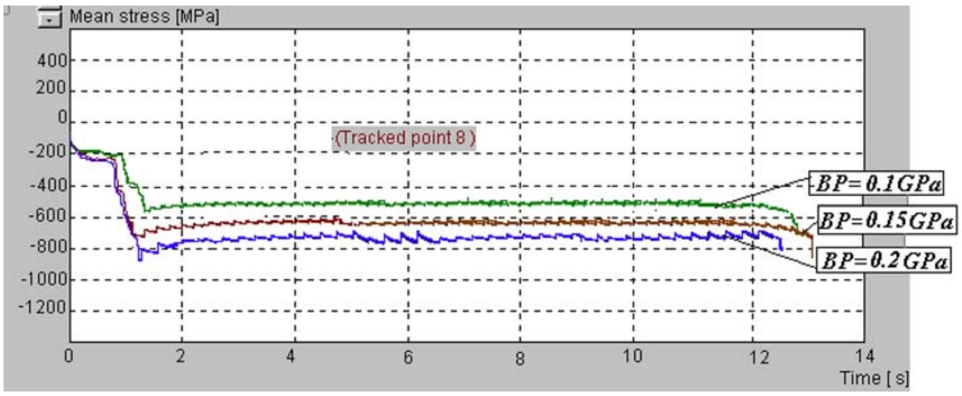


Figure 8 The mean stress history in the point at the inner surface for three different values of back-pressure.

shown in Fig. 7 for three points in the middle and on the inner- and outer surfaces indicated in Fig. 6b. As can be seen the mean stress at the outer surface and middle flow line is similar and has negative value during deformation. At the inner surface, the mean stress changes sign from negative to positive as soon as a particle passed the corner of the die, which is the reason for the cracking starting from the inner surface, as will be discussed in the next paragraph. To create a uniform stress distribution along the cross-section of the sample, back-pressure can be applied. In the presence of back-pressure the mean stress histories for the points at the outer and inner surfaces become the same. The value of a mean stress is negative during deformation what helps to prevent cracking and extrude the low ductile samples. The mean stress history for three different levels of back-pressure for the particle at the inner surface is shown in Fig. 8. Using these results the number of passes in ECAE without fracture can be calculated for any particular material.

4. Prevention of fracture of low ductile materials during ECAE by using back-pressure

Prediction of fracture during plastic deformation based on comparison of plastic strain, ε, accumulated by any particle of material with the critical strain at the same values of temperature, T, and stress index, $\frac{\bar{\sigma}}{\sigma_e}$ [18], where the stress index defined as the ratio of hydrostatic pressure to equivalent shear stress. We will consider here the prediction of fracture during ECAE of Al 2024 using Route A, as this route is the most favorable for crack initiation.

The fracture criterion for monotonic deformation can be written [19] as follows:

$$\omega = \sum_{1}^{N} \int_{0}^{1.15} \frac{a\varepsilon^{a-1}}{\varepsilon_{cr}\left(\frac{\bar{\sigma}}{\sigma_e},\ T\right)} = 1 \tag{1}$$

here N is the number of passes and a is intensity of damage accumulation obtained experimentally [19]. The critical local strain as a function of stress index and temperature is known as a Lower-Bound Ductility (LBD) and is usually obtained experimentally [19]. The LBD diagrams for Al 2024 obtained under shear stress state [20], are shown in Fig. 7. According to this room temperature data, the intensity of damage accumulation, a, is equal to 0.886 and critical strain can be written as:

$$\varepsilon_{cr} = 1.309\ \exp\left(-0.816 * \frac{\bar{\sigma}}{\sigma_e}\right) \tag{2}$$

During ECAE through a 90° die, the particle at the inner surface of the specimen accumulates the equivalent strain equal to 1.15 almost instantly and the stress index changes during deformation from the minimum value in the range given in Table I to the maximum value. Numerical calculation of the integral in Equation 1 for particle number 8 gives the value of damage accumulated during one pass of the ECAE at the inner surface of the sample.

TABLE I Change of stress index and equivalent strain during ECAE for different back-pressures and damage accumulated in one pass

	BP = 0 GPa	BP = 0.1 GPa	BP = 0.15 GPa	BP = 0.2 GPa
Stress index	−1.8 . . . +1.2	−0.8 . . . −2.1	−0.8 . . . −2.5	−0.8 . . . −3.1
Equivalent strain	0.0 . . . 1.15	0.0 . . . 1.15	0.0 . . . 1.15	0.0 . . . 1.15
Damage in one pass	1.37	0.71	0.46	0.31

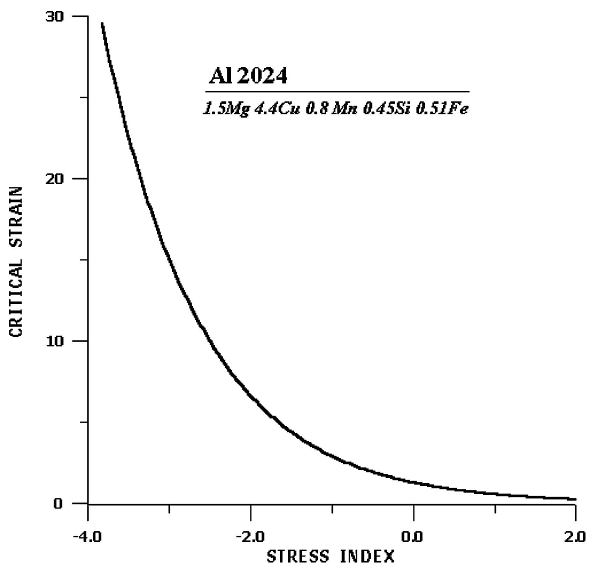


Figure 9 Lower-bound ductility of Al 2024 under shear stress state.

Substituting the value for the integral in Equation 1, one can notice that the specimen should fail during a first pass if the ECAE is performed without back-pressure. It will withstand one, two or three passes (Route A), if the back-pressure applied is 0.1 GPa, 0.15 GPa or 0.2 GPa respectively. Therefore, the increase in back-pressure prevents possible fracture during ECAE and the low ductile material can be subjected to several passes of ECAP with a suitable level of back-pressure defined by calculations.

5. Conclusions

The role of back-pressure during ECAE has been studied. It has been shown that the application of back-pressure eliminates a gap between a specimen and the die and changes the mode of deformation to a simple shear as described theoretically for an ideal rigid-plastic material. The distribution of strain-stress becomes uniform and the low ductile materials can be extruded without failure. The back-pressure as shown effects also the grain size during grain refinement resulting from ECAE. Back-pressure is an important factor for industrial applications of ECAE such as closing of porosity in cast ingots for forging stock and a compacting of light alloys swarf for the following transportation and re-melting.

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