J Mater Sci (2007) 42:1491–1500
DOI 10.1007/s10853-006-0762-8

Finite element analysis of the effect of back pressure during equal channel angular pressing

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Received: 30 May 2006 / Accepted: 4 August 2006 / Published online: 13 January 2007

Abstract There is an increasing interest in applying back pressure during equal channel angular pressing (ECAP) to improve the process for better control of microstructure and property. The effect of increasing back pressure on deformation characteristics during ECAP such as the plastic deformation zone (PDZ) size and strain rate distribution in the PDZ, size of the corner gap and strain distribution on the longitudinal section were analysed by finite element analysis for both the quasi-perfect plastic and strain hardening materials. This investigation revealed that the back pressure influence very differently the PDZ of the quasi-perfect plastic and strain hardening materials. Many beneficial effects of back pressure were observed in the strain hardening material, with reduced PDZ size, dramatically reduced corner gap, and more uniform strain distribution. For the quasi-perfect plastic material, however, the application of increasing back pressure leads to broadening of PDZ and a decrease in strain rate homogeneity.

Introduction

Equal channel angular pressing (ECAP) is a promising process to produce bulk ultra-fine grained materials with unusual mechanical and physical properties [1]. In ECAP, a workpiece is pressed through a die that contains two equal cross-section channels meeting at an angle ϕ, with an outer arc angle φ [2]. The cross-section of the workpiece is not changed after its passage through the die, and this process can be repeated until the accumulated deformation reaches a desired level. In addition to the fundamental work on evolution of microstructure and properties with the passages of ECAP, extensive investigations were also carried out on the estimation of strains imposed on the workpiece [2–4], stress and strain distributions [5–7], and the effects of material and processing parameters [8–10], providing good guidance for successful ECAP of various materials.

Analytical methods were the first to be used to investigate the deformation behavior of the workpiece during ECAP, including strain analysis based on slip line theory and geometric considerations [2–4, 11, 12] and stress analysis based on upper bound theory [13]. Segal derived an analytical expression to estimate the shear strain for a die angle ϕ with a sharp outer corner ($\varphi = 0°$) and concentrated simple shear along the intersection plane. The von Mises equivalent strain in this case is [2]

$$\varepsilon = \frac{2\cot(\phi/2)}{\sqrt{3}} \quad (1)$$

Later, the effect of the outer corner was introduced by Iwahashi et al. [3], and the effective strain per pass can be calculated from ϕ and φ by

$$\varepsilon = \frac{1}{\sqrt{3}}\left[2\cot\left(\frac{\phi}{2}+\frac{\varphi}{2}\right)+\varphi\operatorname{cosec}\left(\frac{\phi}{2}+\frac{\varphi}{2}\right)\right] \quad (2)$$

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The limitation of these analytical approaches is that ideal situations are assumed that there is no friction and the entire cross section of the workpiece undergoes uniform shear deformation as it flows through the intersection zone of the two channels. These analyses also presume that material is quasi-perfect plastic and the workpiece can fill the die completely whether the die corner is sharp or not.

To overcome these limitations, finite element analysis (FEA) has been employed. Compared to the analytical approach, FEA takes into consideration of more realistic material properties and boundary conditions and can provide better guidance for theoretical models and process design. FEA has been applied to investigate the constitutive behavior during deformation [8, 14, 15] and effects of such important factors as die geometry [14, 16–18] and processing variables [14, 16, 19–21]. In general, FEA has produced useful results in simulating die filling and strain uniformity in the deformed volume during a standard ECAP.

However, it is beneficial in some cases to apply a back pressure in the exit channel of the ECAP die as shown in Fig. 1. For difficult-to-work metals, ECAP has to be carried out at higher temperatures to avoid cracking. However, higher processing temperatures promote recovery and recrystallization, which lead to a decrease in crystal defects. This adversely affects the ability of ECAP to refine grains as it depends on accumulated dislocations and other defects to form ultrafine grains. One way to solve the problem is to apply a back pressure during ECAP. Due to the hydrostatic compressive pressure, difficult-to-work metals can be deformed at lower temperatures without cracking, resulting in a finer grain structure. For example, ECAP of magnesium alloys was usually conducted at above 0.5 T_m (the melting point in K of the metal) [22] to prevent cracking during ECAP. It was shown, however, that with the help of a 50 MPa back pressure, ECAP of an AZ31 magnesium alloy could be carried out at a temperature as low as 100 °C (~0.4 T_m) without causing cracks in the processed metal, resulting in finer grains and increased hardness [23]. The application of a back pressure could also improve the uniformity of deformation. The high hydrostatic pressure may cause significant difference in defect storage and this could be critical for some highly non-equilibrium ultra-fine grained materials [24]. Back pressure ECAP was also successfully applied to consolidation of particles at much lower temperatures than those used in conventional sintering, making it valuable in consolidating particles with non-equilibrium structures [25].

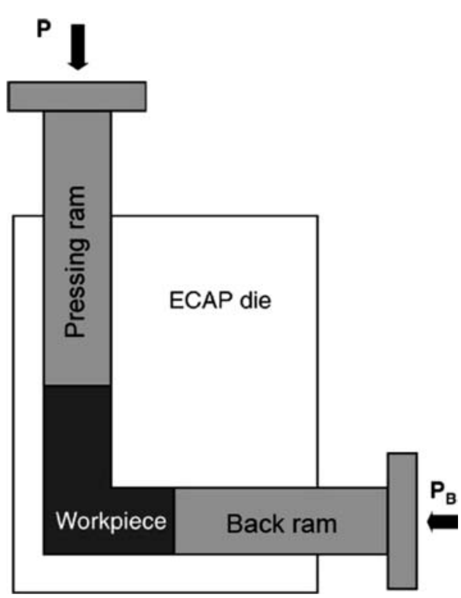

Fig. 1 The back pressure ECAP sets up

In spite of the importance of back pressure in ECAP, especially in processing difficult-to-work metals, its effects have not been well understood and this has in turn limited its effective uses. In one of the few studies, Oh and Kang indicated that the corner gap could be influenced and a higher plastic strain might be achieved by the application of a back pressing plunger [26]. The work of Lapovok suggested that a back pressure may be effective in reducing the internal tensile stress at the inner corner of a ECAP die and revealed back-pressure can effectually control and avoid cracks formation and propagation; can improve the mechanical properties and refine the gain size [27]. It is thus necessary to conduct investigations into the effects of back pressure on the development of strain heterogeneity especially inside the plastic deformation zone (PDZ). This will help determine the optimum magnitude of back pressure for producing uniform deformation and provide guidance for selecting process parameters in back pressure ECAP.

In this paper, FEA was carried out to investigate the effects of back pressure on PDZ, the evolution of the corner gap and strain heterogeneity during one pass of ECAP.

Finite element analysis

Two dimensional plane-strain finite element simulations of ECAP were performed using the commercial elasto-plastic finite element code, MARC. A model die with the geometry of 10×10 mm in cross section, 60 mm in workpiece length, and $\phi = 90°$ and $\varphi = 0°$

was used. The number of initial meshes (four-node isoparametric plane strain elements) was 2400. This number of elements was found to be sufficient to show local deformation of the workpiece by calculating with varying number of elements [7].

Two factors were varied in the simulation: back pressure and material character. Two kinds of materials were utilised to investigate the strain hardening effect. Firstly, 6061Al-T6 was used as a (nearly) non-hardening, i.e. quasi-perfect plastic, material [28, 29]. Secondly, 1100Al was used as a strain hardening material. The stress–strain relationship for 1100Al is $\sigma_s = 173.97\varepsilon^{0.304}$ MPa [30] and for 6061Al is $\sigma_s = 413.68\varepsilon^{0.05}$ MPa [28]. Where σ_s is the flow stress (in MPa), ε denotes the equivalent plastic strain. The elastic properties of both materials are equivalent with a Young's modulus of 70 GPa and a Poisson's ratio of 0.33. The coefficient of friction between the inner surfaces of the die channel and the specimen was taken to be zero, implying a frictionless condition. Cold working steel for modeling the pressing ram and back ram. Pressing ram is controlled by a constant speed of 1 mm s^{-1}. The back pressure was applied through a back pressing ram by edge force and varied from 0 to 250 Mpa which is similar with Lapovok's work [27]. All simulation used automatic remeshing to accommodate large strains and the occurrence of flow localization during the simulation.

Results and discussion

Effect of back pressure on plastic deformation zone (PDZ)

Each time the workpiece is pressed through the die during ECAP, it undergoes severe plastic deformation within a region around the intersection plane of the two channels of the die. This region is defined as the plastic deformation zone (PDZ). The evolution of strain and its uniformity, as well as the resulting microstructure and material properties, depend on the characteristics of PDZ such as the distribution of strain rate. Based on above PDZ definition, it is reasonable to use non-zero strain rate contour to depict PDZ. As a good approximation, the minimum level of strain rate, $\dot{\varepsilon}_m$, within PDZ (in which the strain rate has to be >0), is set to 0.01 s^{-1} which defines the boundary of PDZ. As shown in Fig. 2, the region filled with contour lines is the PDZ, within which each volume element of the workpiece has a non-zero strain rate (i.e. $\dot{\varepsilon} > 0$). The lettered contour lines indicate different equivalent plastic strain rate values (A = 0.010, B = 0.136, C = 0.263, D = 0.389, E = 0.515, F = 0.642, G = 0.768, H = 0.895, I = 1.021, J = 1.147, K = 1.274 and L = 1.400 s^{-1}). Outside PDZ, the volume elements of the workpiece are not deforming and thus have a strain rate value close to 0 (i.e. $\dot{\varepsilon} \rightarrow 0$).

Figures 2a, b show the distribution of the equivalent plastic strain rate for the quasi-perfect plastic and strain hardening materials, respectively, during ECAP without back pressure. For quasi-perfect plastic material, the high $\dot{\varepsilon}$ area is located in a narrow band near the intersection plane, indicating that most of the plastic deformation takes place in this region. $\dot{\varepsilon}$ is higher at the inner corner than in the centre but the highest $\dot{\varepsilon}$ is located at the outer corner; the central area is broader and consequently the total plastic strain remains almost uniform along the workpiece width. In contrast, PDZ of the strain hardening material is larger, consisting of two regions: one emanating from the inner die corner and separating into two at the outer corner where the corner gap forms, and the other near the end of the inlet channel. The equivalent plastic strain rate $\dot{\varepsilon}$ reaches a local maximum at the inner corner. At the outer surface, $\dot{\varepsilon}$ is noticeably higher at the finishing end of the outer

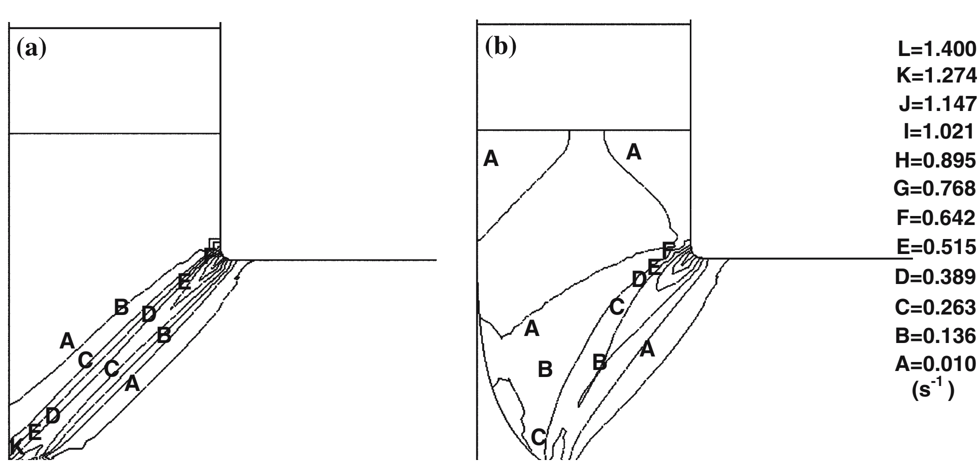

Fig. 2 The distribution of the equivalent plastic strain-rate in (**a**) the quasi-perfect plastic material (6061Al-T6) and (**b**) the strain hardening material (1100 Al) with no back pressure

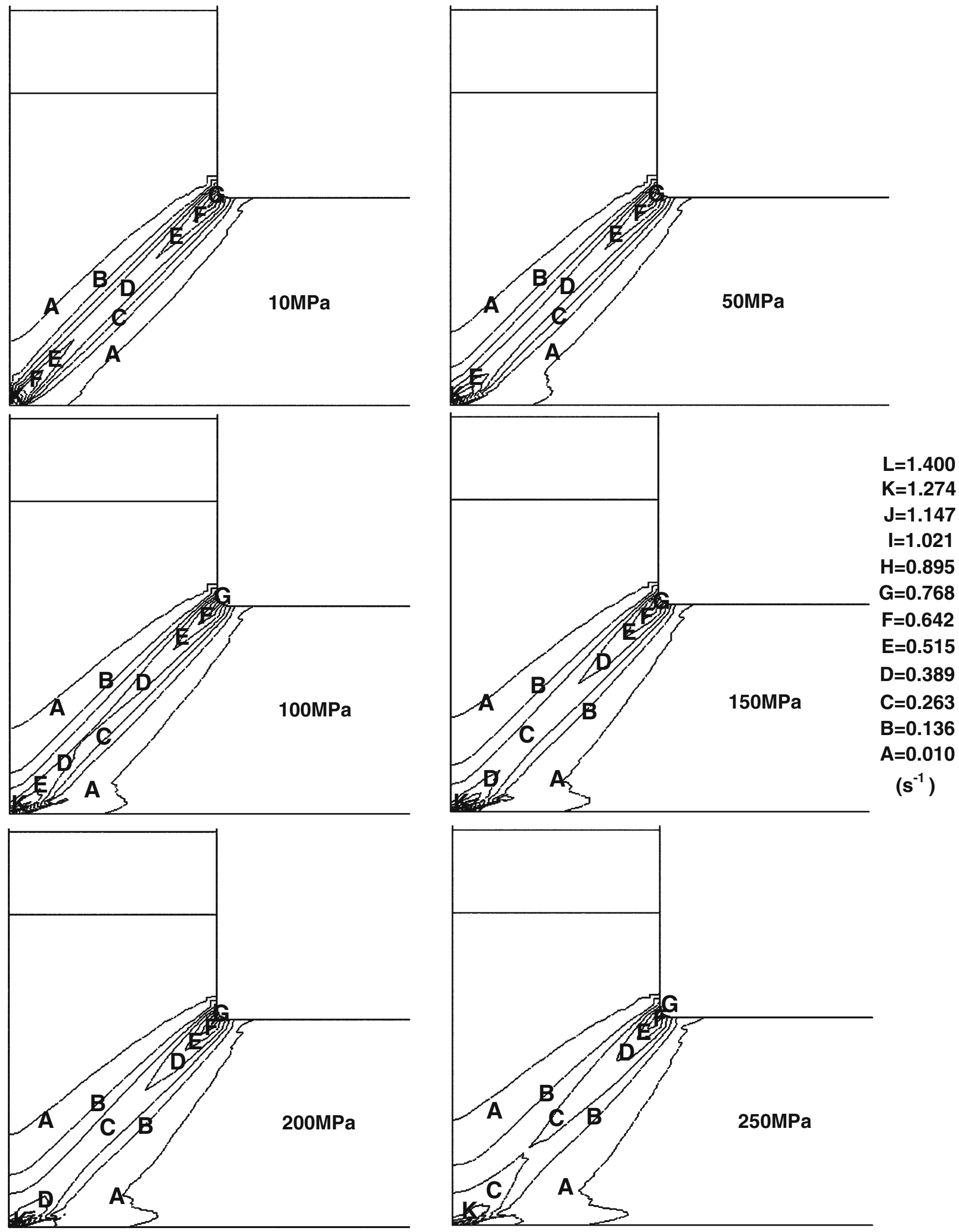

Fig. 3 Influence of back pressure on strain rate distribution in the quasi-perfect plastic material (6061Al-T6). The numbers in the figure indicate the levels of applied back pressure

corner arc than at the starting end. It is clearly that the shape of PDZ is symmetry from relative magnitudes of $\dot{\varepsilon}$ in the quasi-perfect plastic material, while strain hardening material not, as is shown in Fig. 2. These results are similar to those obtained by Li et al. [10].

The influence of the back pressure on the distribution of the equivalent plastic strain rate within the PDZ is shown in Figs. 3 and 4 for the quasi-perfect plastic and strain hardening materials, respectively. Significant differences are observed between the two materials. In the quasi-perfect plastic material, the size of PDZ appreciably broadens with increasing back pressure. The broaden regions mostly local at the outer corner, filled with A contour line. Also, the value of the equivalent plastic strain rate $\dot{\varepsilon}$ increases considerably, especially at the outer corner. In contrast, the size of PDZ, in particular the part in the inlet channel, in the strain hardening material gradually shrinks with increasing back pressure. Back pressure equals to 100 MPa, the size of PDZ obtains the smallest. And then PDZ broadens with the increase back pressure, which seems the evolution of PDZ in quasi-perfect plastic material. $\dot{\varepsilon}$ in PDZ is higher at the outer and inner corners than in the centre. With the increase in back pressure, the equivalent plastic strain rate in the

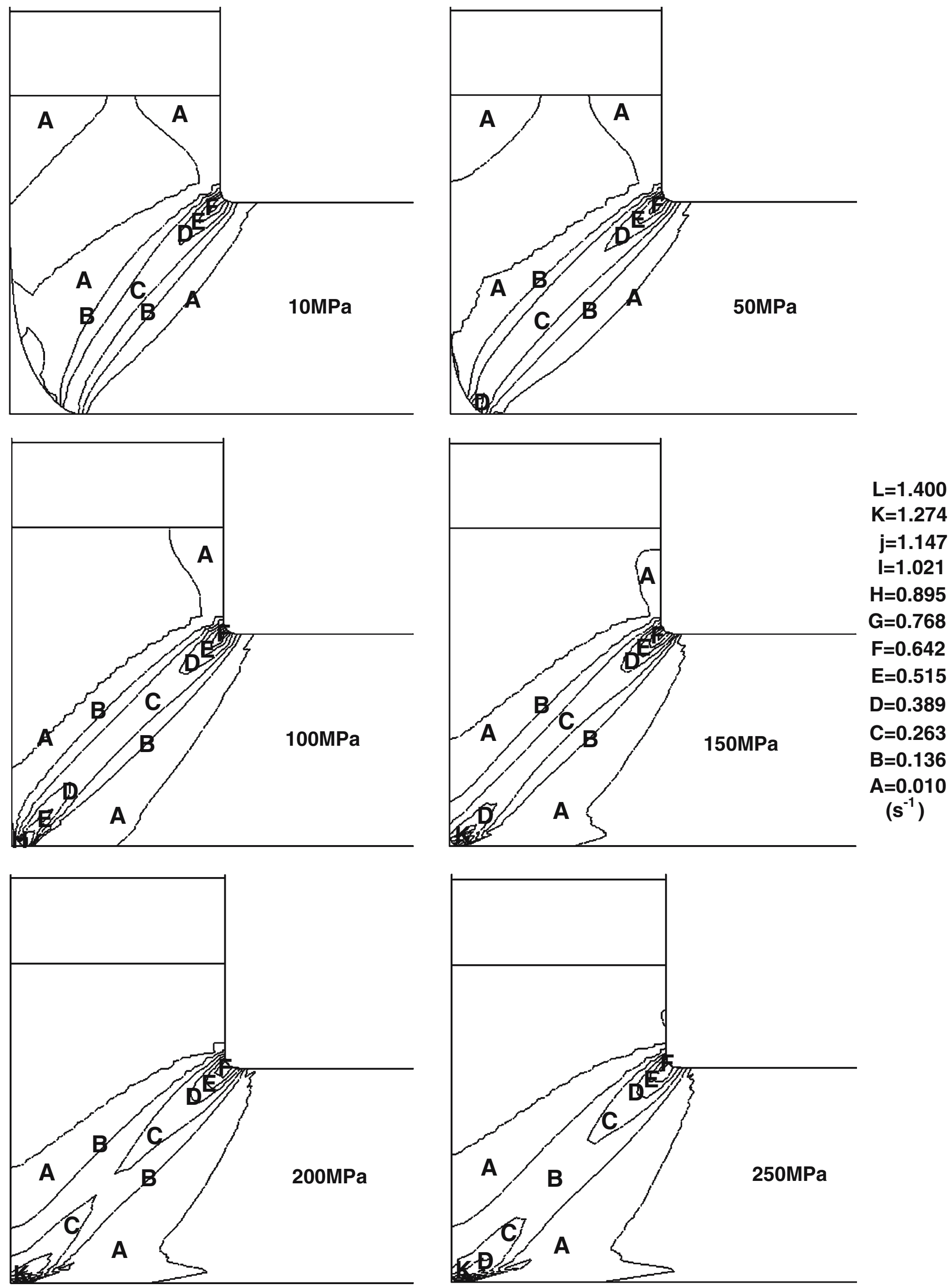

Fig. 4 Influence of back pressure on strain rate distribution in the strain hardening material (1100 Al). The numbers in the figure indicate the levels of applied back pressure

outer corner rises noticeably. The symmetry of the PDZ improves with increasing back pressure. Lapovok [27] reveals a difference between the shapes of PDZ in Al 2124-T851 after one pass of ECAP without back pressure and with 200 MPa of back pressure. According to his experiment, a PDZ in the shape of a fan is formed without back pressure, however, with 200 MPa of back pressure a PDZ is a narrow band near the intersection plane. All of his results are consistent with simulation in the strain hardening material.

To achieve an overview of the PDZ evolution with increasing back pressure, the area of PDZ as defined by the contour lines of $\dot{\varepsilon} = 0.01\ s^{-1}$ is estimated and plotted in Fig. 5 as a function of the level of back pressure for both the quasi-perfect plastic and the strain hardening materials. It is clearly seen that the area of PDZ in the strain hardening material continuously decreases with increasing back pressure and until back pressure is 100 MPa, the PDZ achieves the smallest, then the PDZ broadens again till the highest back pressure applied in the present investigation. For ideal ECAP deformation, simple shear appears in a narrow band at the intersection, with the width of the band approaching zero [2, 4]. It is thus reasonable to

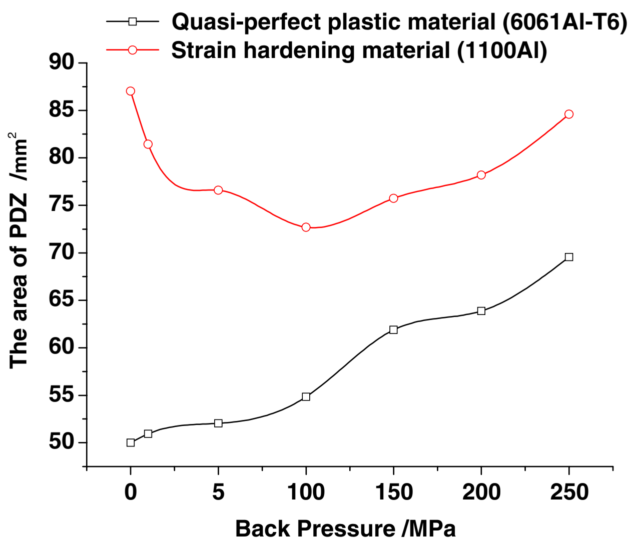

Fig. 5 Influence of back pressure on the area of PDZ for the quasi-perfect plastic material (6061Al-T6) and the strain hardening material (1100Al)

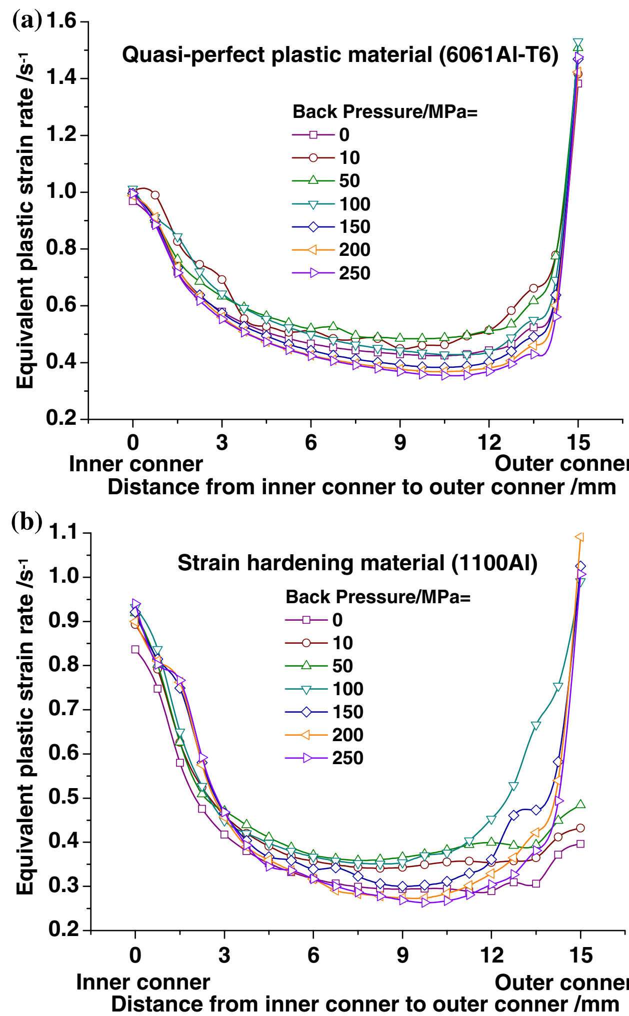

Fig. 6 The effect of back pressure on the distribution of strain rate from the inner corner to outer corner along the intersection line of the two channels for (**a**) the quasi-perfect plastic material (6061Al-T6) and (**b**) the strain hardening material (1100Al)

consider that the narrower this shearing band (i.e. PDZ), the closer the deformation to the ideal simple shear and the better the result of ECAP in controlling microstructure of the workpiece. Therefore, the beneficial effect of back pressure on reducing the PDZ area is demonstrated for the strain hardening material. However, the same conclusion cannot be drawn for the quasi-perfect plastic material, as illustrated in Figs. 3 and 5.

To appreciate the effect of back pressure on the strain rate distribution in PDZ, the strain rate distribution from the inner corner to outer corner along the intersection line of the two channels is shown as a function of back pressure in Fig. 6 for the quasi-perfect plastic and strain hardening materials. The homogeneity of strain rate in the quasi-perfect plastic material appears to get worse with the application of back pressure because it increases the strain rate at the inner and outer corners of the deformation zone. Corresponding to its larger deformation zone, the strain rates in the strain hardening material are generally lower than those in the quasi-perfect plastic material. On the other hand, the beneficial effect of back pressure on the strain rate distribution is observed in the strain hardening material. As the PDZ area decreases in the beginning with increasing back pressure, until 100 MPa back pressure, the overall strain rate along the intersection line increases and the strain rate distribution becomes more uniform and symmetry because the strain rate increase upon the application of back pressure is greater in the low strain rate region near the outer corner. When back pressure exceeds 100 MPa, the homogeneity of strain rate appears to get worse because it increases the strain rate at the outer corners of the deformation zone.

This is an interesting phenomenon that the size of PDZ broadens and the homogeneity of strain rate gets worse with increasing back pressure in two different materials, which has never been reported. This might be due to back pressure attributed to the increased constraint force and to decrease the material flow, especially at the workpiece surface. Moreover, back pressure results in the stress concentration, in turn; plastic deformation increases locally, in particular in the bottom region of the workpiece close to the outer corner of the die; so the local maximum strain rate is focus on the end of the intersection line; with the increasing of back pressure, the trend more obviously, thus the homogeneity of strain rate gets worse.

Oh and Kang [26] believe that back pressure acts as a friction, just larger than friction force. Compared our results with the previous work [10, 26], the same conclusion can be drown. Friction does affect the strain rate distribution in the PDZ just like back pressure. Friction leads to increases in the maximum of $\dot{\varepsilon}$ at the outer corner in the case of the perfectly plastic material and near the finishing end of the arc at the outer curvature in the strain hardening material becomes more symmetric and less dependent on material response. The effect of friction on the plastic strain rates as stated above translates directly with its effect on the accumulated plastic strains. For example, the friction-induced higher equivalent plastic strains in the bottom of the workpiece in the case of perfectly plastic material. A lot of things about this interesting phenomenon still need be studied further.

Effect of back pressure on the corner gap

The corner gap is an important indicator of the deformation characteristics of PDZ, and may even be used to evaluate the quality of ECAP processing [26]. As has been shown in Fig. 2, the corner filling behaviours without back pressure can be considerably different between the quasi-perfect plastic and strain hardening materials. The corner gap between the die and the workpiece is large in the strain hardening material which has high strain hardening behaviour and relatively small in the quasi-perfect plastic material with low strain hardening behaviour. For the quasi-perfect plastic material, the workpiece deforms as the ram presses and the die corner is filled nearly completely by the material of the workpiece. In the strain hardening material, however, the corner gap between the die and the workpiece is much more significant with an asymmetrical shape. That is, the corner gap along the entry side is longer that that along the exit side. This is attributed to the difference in deformation resistance between the volume elements at the inner corner and those at the outer corner, resulting from their different extents of deformation. The volume elements at the outer corner experience less deformation and are thus softer than those at the inner corner and flow faster.

The shape change of the corner gap with increasing back pressure can be observed in Figs. 3 and 4. No obvious corner gap is seen in the quasi-perfect plastic material at any level of back pressure. For the strain hardening material, however, the corner gap shrinks and tends to become symmetrical with increasing back pressure, which is similar with the evolution in the symmetry of PDZ. Figure 7 summarizes the change of the corner gap in the two materials with increasing back pressure. In strong contrast to the unchanging zero corner gap area in the quasi-perfect plastic material, the corner gap area in the strain hardening material continuously decreases until disappears completely with increasing back pressure. The reason is that the deformation of the workpiece at outer corner aggravates with the increasing back pressure, and the workpiece at outer corner becomes as hard as the inner corner, meanwhile back pressure slows down the metal flowing velocity at the inner corner, so the shape and asymmetry of corner gap continuously decrease, Fig. 8 clearly reveals the evolution of corner gap for strain hardening material without back pressure and with 50 MPa of back pressure, which showing metal flow in different increments. When back pressure reaches 200 MPa, the corner gap disappears completely in the strain hardening material. In the previous work [26, 27], it is indicated that back pressure can effectually reduce the corner gap.

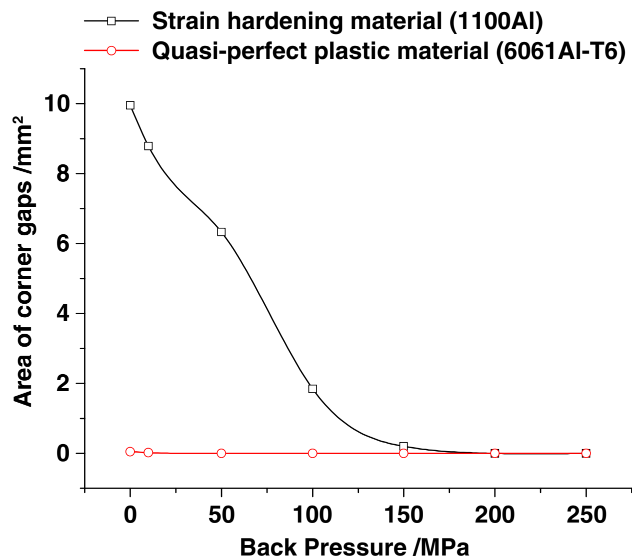

Fig. 7 The effect of back pressure on the corner gap in the quasi-perfect plastic material (6061Al-T6) and the strain hardening material (1100Al)

The effect of back pressure on heterogeneity in strain distribution

As a result of strain accumulation as the workpiece passing through PDZ, the plastic strain varies at different volume elements of the workpiece in both the quasi-perfect plastic and the strain hardening materials. On the longitudinal section, three distinct regions can be identified from left to right along the workpiece axis: the short non-steady deformation zones at the head and tail of the workpiece, and the longer steady deformation region in the middle, as shown in Fig. 9. The area of the strain heterogeneity at

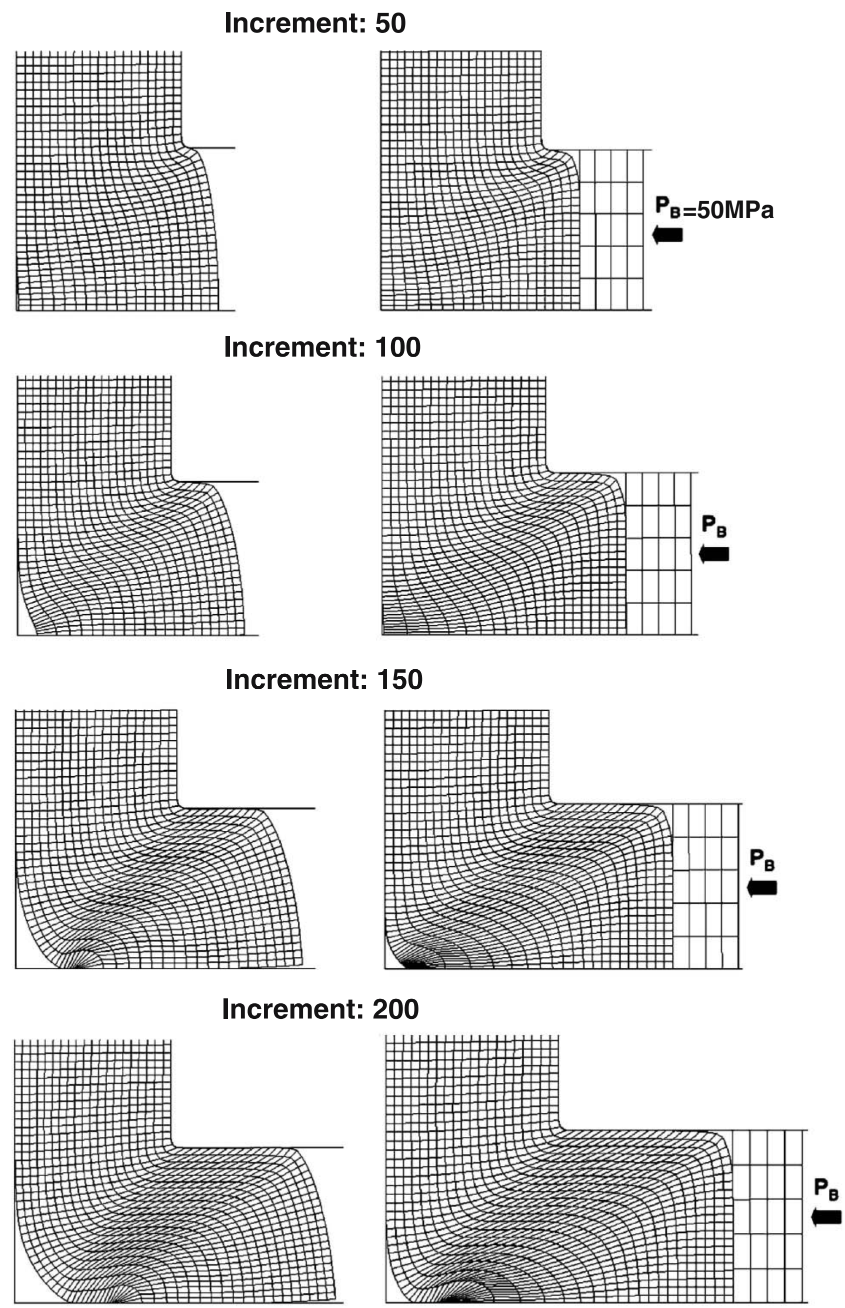

Fig. 8 The formation of corner gap for strain hardening material which showing metal flow in two different cases. Back pressure is 50 Mpa

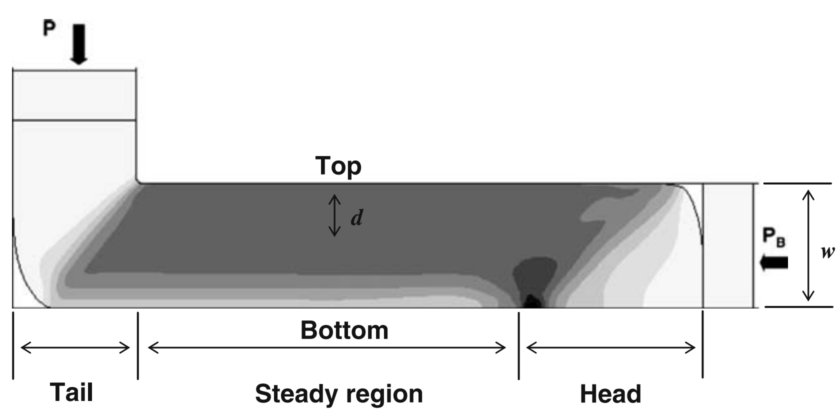

Fig. 9 The three regions on the longitudinal section of a ECAP processed workpiece showing the unsteady deformation zones at the head and tail and the steady deformation zone in the middle. The contours are for equivalent plastic strain

tail part is similar in different cases, while the area at head part is completely different for these two materials. Figure 10 shows the relation of back pressure and the area of strain heterogeneity at head part in two materials. It is seen clearly that in the quasi-perfect plastic material, the area of strain heterogeneity at head part does not change. But for strain hardening material, the area of the strain heterogeneity at head part obviously decreases with the increasing back pressure; at 150 MPa back pressure, the area is the smallest and close to the level of quasi-perfect plastic material, that is, the region of steady state broadens.

The strain is uniform along the horizontal axis within this steady-state region; however, deformation heterogeneity still exists along the height direction. Figure 11 shows the distributions of the equivalent plastic strain plotted as a function of the relative distance from the top surface of the workpiece, *d*/*w*, where *d* is the distance from the top surface and *w* (=10 mm) is the height of the pressed workpiece.

For the quasi-perfect plastic material (Fig. 11a), the value of equivalent plastic strain, ε_e, is homogeneous from the top surface ($d = 0$) to the vicinity of the bottom ($d/w = \sim 0.8$), and the back pressure seems to have little effect on the value of ε_e. This can be attributed to that the distribution of the equivalent plastic strain rate is located in a narrow band near the intersection plane, and the central area of PDZ broadens with increasing back pressure and consequently the total plastic strain remains almost uniform along the workpiece width. In the bottom region (from $d/w = \sim 0.9$ to $d/w = 1$), however, ε_e increases rapidly to a much higher level, and back pressure enhances this

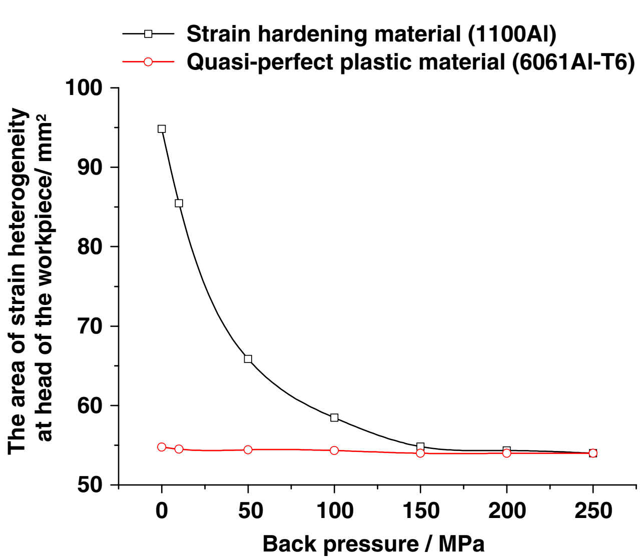

Fig. 10 Relation of back pressure and the area of strain heterogeneity at head part in two materials

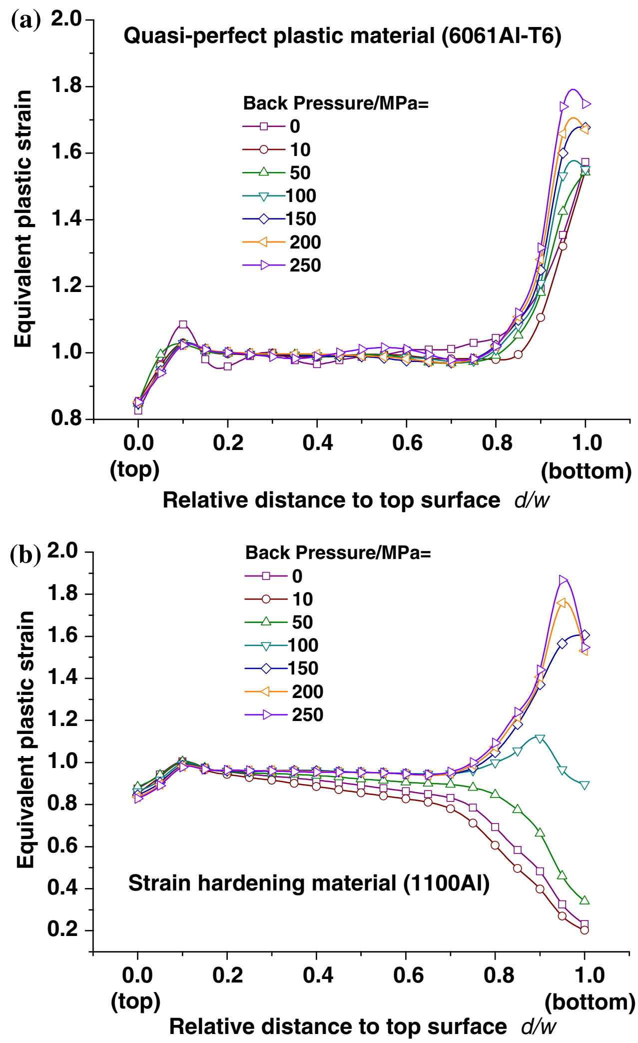

Fig. 11 The equivalent plastic strain distribution along the workpiece height in the steady-state region of (**a**) the quasi-perfect plastic material (6061 Al-T6) and (**b**) the strain hardening material (1100Al)

strain increase, owing to the increase in deformation severity at the outer corner of PDZ and with the increase in back pressure. The heterogeneous deformation is constrained to the 1/10 of the thickness near the bottom surface of the workpiece and the remaining majority of the workpiece deforms quite homogeneously.

Things are quite different in the strain hardening material (Fig. 11b), the equivalent plastic strain ε_e is higher in the vicinity of the top surface (from $d/w = 0$ to $d/w = 0.1$) and decreasing dramatically near the bottom (from $d/w = 0.8$ to $d/w = 1$). The equivalent plastic strain ε_e changes moderately in the middle part of the workpiece, increasing towards the bottom at higher back pressures. ε_e within this steady-state region reaches the best homogeneous at 100 MPa back pressure. Then ε_e near the bottom (from d/w = 0.9 to d/w = 1) obviously rises with the increasing back pressure. The general trend is similar with the quasi-perfect plastic material. The reasons are that the strain rate distribution along the intersection line becomes more uniform and symmetry with the increasing of back pressure till 100 Mpa. When back pressure exceeds 100 MPa, the homogeneity of strain rate appears to get worse, as in the quasi-perfect plastic material

In the work of Oh and Kang [26], the equivalent plastic strain of the bottom part is increased to 2.5 with back pressure. Strain value of 2.5 is bigger than our result and far from uniform deformation. But, it is possible to control by reducing the back pressure. Therefore, the best conditions for the ECAP process will be studied further.

Summary

The effect of back pressure on deformation characteristics during ECAP was analysed using finite element analysis for both quasi-perfect plastic material (6061Al-T6) and strain hardening material (1100Al), which shows very different effect in the two different materials.

(1) In the quasi-perfect plastic material, with the increase of back pressure, the size of PDZ appreciably broadens; the value of the equivalent plastic strain rate obviously increases, especially at the outer corner; and the homogeneity of strain rate becomes worse.
(2) In the strain hardening material, with increasing back pressure, the size of PDZ shrinks, after 100 MPa back pressure, it obviously broadens; the overall strain rate along the intersection of the two channels increases; and the heterogeneity of strain rate distribution decreases until 100 MPa back pressure, and then increase with the rising of back pressure.
(3) No obvious corner gap was observed in the quasi-perfect plastic material with or without the application of a back pressure; In the strain hardening material, the corner gap shrinks and tends to become more symmetrical with increasing back pressure; at 200 MPa back pressure, the corner gap disappears.
(4) Heterogeneous deformation in the quasi-perfect plastic materials is constrained to 1/10 of the thickness near the bottom of the workpiece while the remaining material deform uniformly, and this is apparently not influenced by the application of back pressure.
(5) The application of a back pressure observably influences the strain homogeneity of the strain hardening material, the deformation heterogeneity decreases continuously with increasing back pressure, ε_e reaches the best homogeneous at 100 MPa back pressure, then ε_e takes on a similar trend with the quasi-perfect plastic materials.

Acknowledgements The work is supported partially by the National Nature Science Foundation of China under Grant No. 50474028.

References

1. Valiev RZ, Islamgaliev RK, Alexandrov IV (2000) Prog Mater Sci 45:103
2. Segal VM, Reznikov VI, Drobyshevkiy AE, Kopylov VI (1981) Russ Metall 1:99
3. Iwahashi Y, Wang J, Horita Z, Nemoto M, Langdon TG (1996) Scr Mater 35:143
4. Xia K, Wang J (2001) Metall Mater Trans 32A:2639
5. Prangnell PB, Harris C, Roberts SM (1997) Scr Mater 37:983
6. Bowen JR, Gholinia A, Roberts SM, Prangnell PB (2000) Mater Sci Eng A287:87
7. Kim HS (2001) Mater Sci Eng A315:122
8. Kim HS, Seo MH, Hong SI (2000) Mater Sci Eng A291:86
9. Kim HS, Seo MH, Hong SI (2001) J Mater Proc Technol 113:622
10. Li S, M. Bourke AM, Beyerlein IJ, et al (2004) Mater Sci Eng A382:217
11. Segal VM (1999) Mater Sci Eng A271:322
12. Segal VM (2003) Mater Sci Eng A345:36
13. Lee DN (2000) Scr Mater 43:115
14. Semiatin SL, Delo DP, Shell EB (2000) Acta Mater 48:1841
15. Moon BS, Kim HS, Hong SI (2002) Scr Mater 46:131
16. Bowen JR, Gholinia A, Roberts SM, Prangnell PB (2000) Mater Sci Eng A287:87
17. Suh JY, Kim HS, Park JW, Chang JY (2001) Scr Mater 44:677
18. Park JW, Suh JY (2001) Metall Mater Trans 32A:3007
19. Kim HS, Seo MH, Hong SI (2001) J Mater Process Technol 113:622
20. Delo DP, Semiatin SL (1999) Metall Mater Trans 30A:1391
21. Zhernakov VS, Budilov IN, Raab GI, Alexandrov IV, Valiev RZ (2001) Scr Mater 44:1765
22. Yamashita A, Horita Z, Langdon TG (2000) Metall Mater Trans A300:142
23. Xia K, Wang JT, Wu X, Chen G, Gurvan M (2005) Mater Sci Eng A410–411:324
24. Zehetbauer MJ, Steiner G, Schafler E, Korznikov A, Korznikova E (2006) Mater Sci Forum, 503–504:57
25. Xia K, Wu X (2005) Scr Mater 53:1225
26. Oh SJ, Kang SB (2003) Mater Sci Eng A343:107
27. Ye. Lapovok R (2006) Mater Sci Forum 503–504:37
28. Lee DN (1996) Plastic Deformation Theory, Moonoondang, Seoul, p 92
29. Hong SI, Gray III GT, Wang Z (1996) Mater Sci Eng A221:38
30. Altan T, Oh SI, Gegel HL (1983) Metal forming fundamentals and applications, American society for metals, Ohio, Carnes Publication Services, p 58 and p 237