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A Finite Element Investigation into the Changing Channel Angular Extrusion of Brass Alloy

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Abstract. This study investigates a novel changing channel angular (CCA) extrusion process, in which high strains are induced within the billet by passing it through a series of channels of unequal cross-sections arranged such that they form specified internal angles. Using commercial DEFORM™ 2D rigid-plastic finite element code, the plastic deformation behavior of CuZn37 brass alloy is examined during one-turn and two-turn CCA extrusion processing in dies with internal angles of ϕ=90°, 120°, 135° or 150°, respectively. The simulations focus specifically on the effects of the processing conditions on the effective strain, the rotation angle and the effective stress induced within the extruded billet. The numerical results provide valuable insights into the shear plastic deformation behavior of CuZn37 brass alloy during the CCA extrusion process.

Introduction

In general, rolling, extrusion and forging processes subject the working material to very high strains. The resulting plastic deformation causes a significant change in the physical and mechanical properties of the material. Accordingly, there are significant benefits to be gained from deforming metallic alloys under very high levels of plastic strain. The equal channel angular (ECA) extrusion process (also known as equal channel angular pressing (ECAP)) was first developed by Segal *et al.* [1-2] as a means of inducing large plastic strains within metallic workpieces without causing a significant change in their outer dimensions. More recently, Liu *et al.* [3] presented a novel changing channel angular (CCA) extrusion method designed to reduce the tensile stress within the workpiece and to increase the hydrostatic pressure during the extrusion process.

Kim [4] used commercial DEFORM™ 2D software to perform a finite element analysis (FEA) investigation into the formation of corner gaps between the die and the workpiece during the plane strain ECAP process. In analyzing the multiple-pass ECAP process, Figueiredo *et al.* [5] neglected the strain path effect and predicted the material deformation behavior in each pass using a single stress-effective strain curve. Meanwhile, the present authors [6] applied a FE method to investigate the plastic deformation behavior of Ti-6Al-4V titanium alloy during one- and two-turn ECA extrusion.

The current study uses DEFORM™ 2D FE code to investigate the plastic deformation behavior of CuZn37 brass alloy during one- and two-turn CCA extrusion processing, in which high strains are induced within the billet by passing it through a series of channels of unequal cross-sections arranged such that they form specified internal angles. The simulations focus particularly on the effects of the CCA processing conditions on the distributions of the effective strain, rotation angle and effective stress, respectively, within the extruded workpiece.

Analytical method

According to Kim and Yang [7], the FE formulation for rigid-plastic deformation in a material subject to work hardening has the form

$$\int_{V^w}(\bar{\sigma}+\alpha\Delta t\dot{\bar{\varepsilon}}H')\delta\dot{\bar{\varepsilon}}dV+K\int_{V^w}\dot{\varepsilon}_V\delta\dot{\varepsilon}_V dV-\int_{S_f^w}(f_i+\alpha\Delta f_i)\delta v_i dS=0 \qquad (1)$$

where $\bar{\sigma} = \sqrt{(3/2)\sigma'_{ij}\sigma'_{ij}}$, $\dot{\bar{\varepsilon}} = \sqrt{(2/3)\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}}$ and $\dot{\varepsilon}_v = \dot{\varepsilon}_{ii}$. Additionally, K, σ'_{ij}, H' and α are the penalty constant, the deviatoric stress, the strain-hardening rate and the work-hardening effect constant ($0 \le \alpha \le 1$), respectively. Finally, V^w and S_f^w are the volume and tractional boundary surface of the workpiece, respectively.

The DEFORM^{TM} FE 2D simulations performed in this study are based on a flow formulation approach using an updated Lagrangian procedure. The nonlinear equations in the FE software are solved using a direct iteration method combined with the Newton-Raphson scheme. In the solution procedure, the direct iteration method is used to generate a suitable initial estimate for the Newton-Raphson method, which is then employed to obtain a rapid convergence to the final solution. The termination criteria specified for the iteration procedure are as follows: a velocity error norm of $\|\Delta \mathbf{v}\| / \|\mathbf{v}\| \le 0.001$ and a force error norm of $\|\Delta F\| / \|F\| \le 0.01$, where $\|\mathbf{v}\|$ is $(\mathbf{v}^T \mathbf{v})^{1/2}$.

Simulation process analysis and discussion

The current simulations are based upon the following assumptions: (1) both the container and the die are rigid bodies; (2) the extrusion billet is a rigid-plastic material; and (3) the friction factors between the extrusion billet and the ram, container and die are constant. Fig. 1 presents the stress-strain relationship for the current CuZn37 brass alloy. Meanwhile, Fig. 2 illustrates the various CCA die set configurations. As shown, the billets are pressed through channels of unequal cross-sections oriented with internal angles of ϕ=90°, 120°, 135° or 150°, respectively. For each orientation angle, the simulations consider both one-turn and two-turn extrusion processing.

Flow Stress = f (Temperature =600°C, Strain Rate = 0.3s^{-1}, Strain) (MPa)

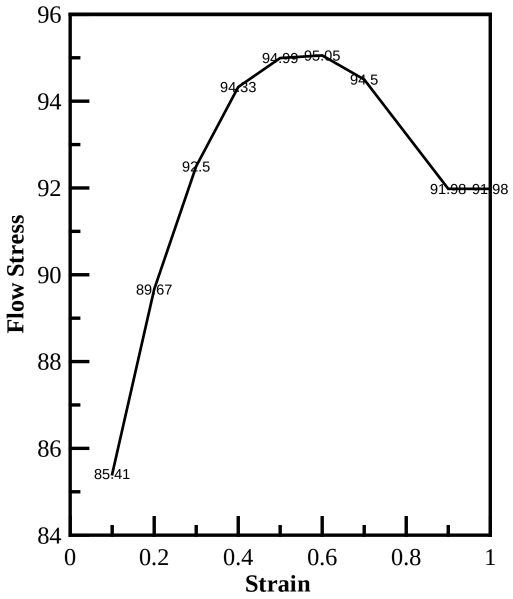
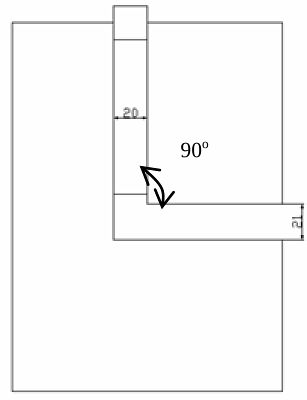


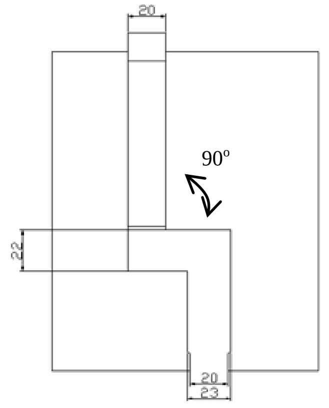
Fig. 1 Stress-strain relationship of CuZn37 brass alloy.

Table 1 summarizes the simulation results obtained for the effective strain induced in the CuZn37 alloy during CCA extrusion processing under different channel orientation angles, friction factors and numbers of turns. Note that the temperature and strain rate remain constant at 600 °C and 0.3 1/s, respectively. The effective strain results are also presented in graphical form in Fig. 3. It is observed that the two highest effective strain values are 11.80 mm/mm and 8.34 mm/mm, respectively, corresponding to simulation cases #3 and #6 in Table 1, respectively. Thus, it is apparent that a greater effective strain is induced in the CuZn37 brass alloy workpiece by performing CCA extrusion with an orientation angle of ϕ=90 and a friction factor of m=0.6.

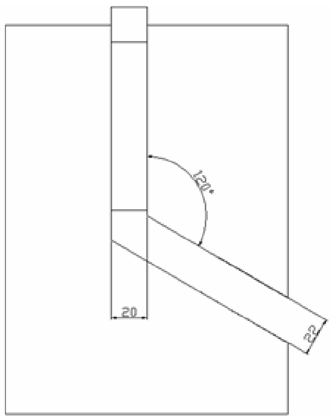
Furthermore, it is found that one-turn extrusion induces a greater effective strain in the billet than two-turn extrusion.



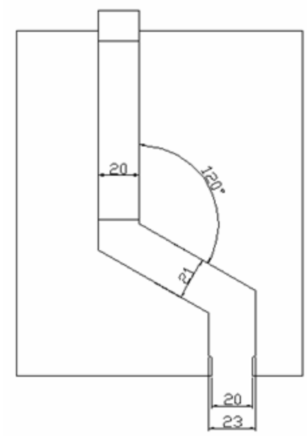
(a) ϕ=90° one turn



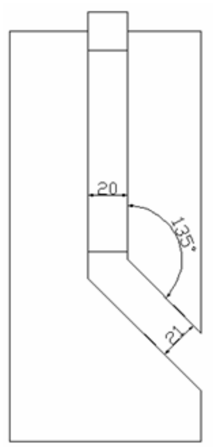
(b) ϕ=90° two turn



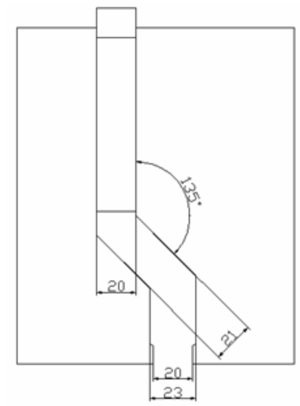
(c) ϕ=120° one turn



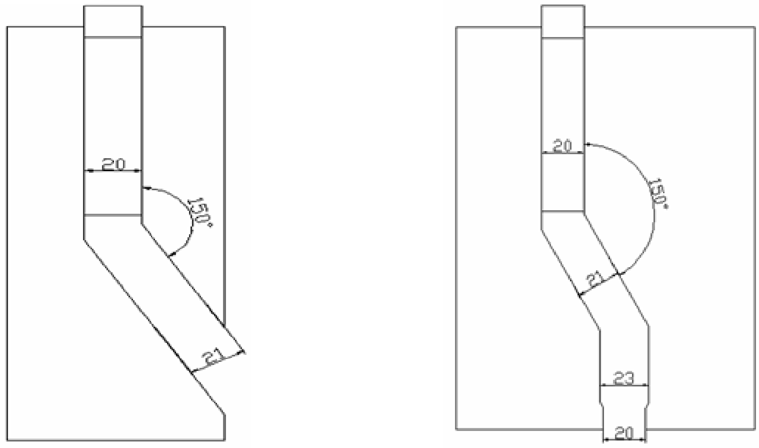
(d) ϕ=120° two turn



(e) ϕ=135° one turn



(f) ϕ=135° two turn



(g) ϕ=150^o one turn (h) ϕ=150^o two turn

Fig. 2 Schematic illustration of CCA extrusion configurations considered in present simulations

Table 1 Effective strain induced in CuZn37 brass alloy during CCA extrusion processing with different channel orientation angles, friction factors and numbers of turns.

No.	ϕ (^{o})	Friction factor	T(^{o}C)	Strain rate (1/s)	Effective strain (mm/mm)	Turn
1	90	0.2	600	0.3	5.11	one
2	90	0.4	600	0.3	6.85	one
3	90	0.6	600	0.3	11.80	one
4	90	0.2	600	0.3	4.04	two
5	90	0.4	600	0.3	6.58	two
6	90	0.6	600	0.3	8.34	two
7	120	0.2	600	0.3	1.27	one
8	120	0.4	600	0.3	1.33	one
9	120	0.6	600	0.3	1.76	one
10	120	0.2	600	0.3	1.98	two
11	120	0.4	600	0.3	2.60	two
12	120	0.6	600	0.3	4.47	two
13	135	0.2	600	0.3	1.44	one
14	135	0.4	600	0.3	1.83	one
15	135	0.6	600	0.3	2.61	one
16	135	0.2	600	0.3	1.12	two
17	135	0.4	600	0.3	2.28	two
18	135	0.6	600	0.3	2.43	two
19	150	0.2	600	0.3	1.00	one
20	150	0.4	600	0.3	1.44	one
21	150	0.6	600	0.3	2.15	one
22	150	0.2	600	0.3	0.79	two
23	150	0.4	600	0.3	0.91	two
24	150	0.6	600	0.3	1.86	two

Figures 4(a) and 4(b) illustrate the rotation angle distributions of the brass alloy in one-turn CCA extrusion with a friction factor of m=0.2 and channel orientation angles ϕ=90^o and ϕ=135^o, respectively. As shown, in the case of an orientation angle of ϕ=90^o, the maximum rotation angle occurs in the upper region of the billet as it is extruded toward the die exit. Conversely, in the case of an orientation angle of ϕ=135°, the maximum rotation angle occurs in the lower region of the billet as it exits the die. Furthermore, comparing the two figures, it is apparent that an orientation angle of ϕ=90° induces a greater rotation angle within the workpiece than an angle of ϕ=135°.

Figures 5(a) and 5(b) show the effective stress distributions in the brass alloy under two-turn CCA extrusion with a friction factor of m=0.2 and channel orientation angles of ϕ=120° and ϕ=150°, respectively. In two-turn CCA extrusion processing, the effective stress induced in the billet reduces as the billet passes around the second turn in the die set. Consequently, the tensile stress is reduced and the hydrostatic pressure is increased. The magnitude of the maximum effective stress is independent of the channel orientation angle.

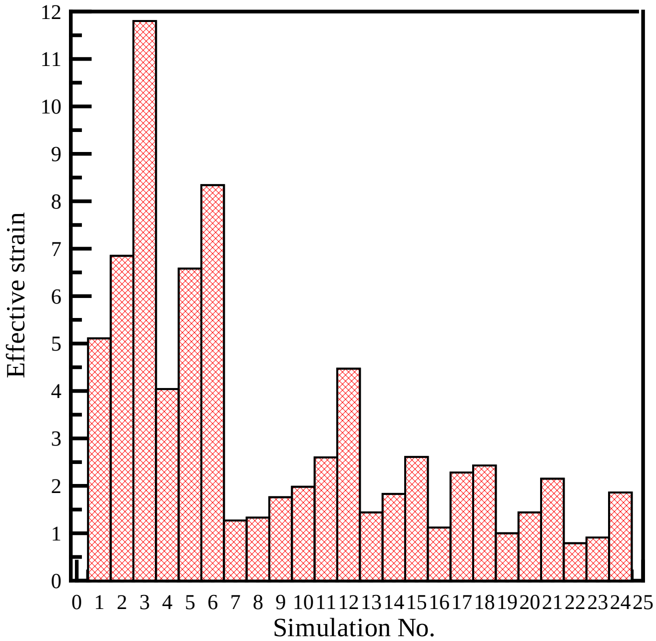
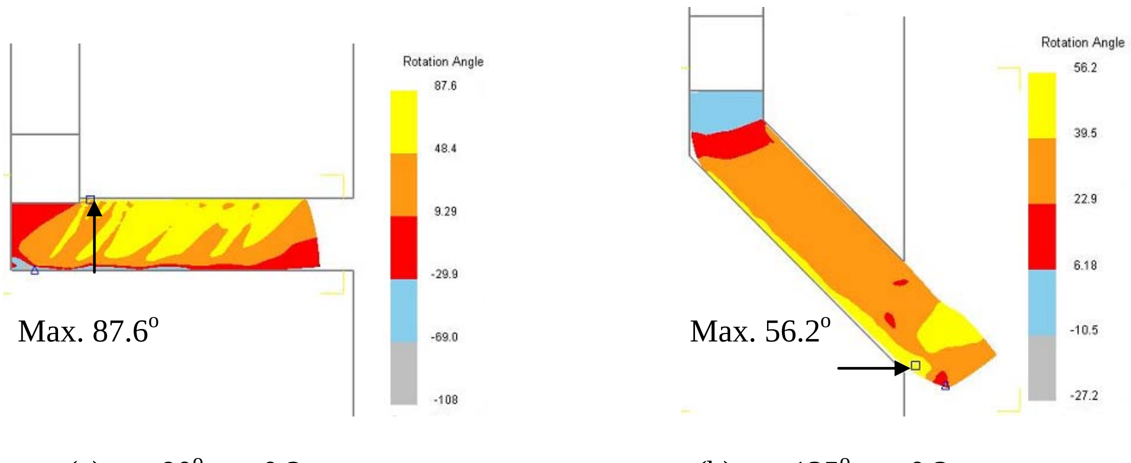


Fig. 3 Induced effective strain for simulation conditions summarized in Table 1.



(a) ϕ=90°, m=0.2, one turn (b) ϕ=135°, m=0.2, one turn

Fig. 4 Distribution of rotation angle in CuZn37 brass alloy following one-turn CCA extrusion processing

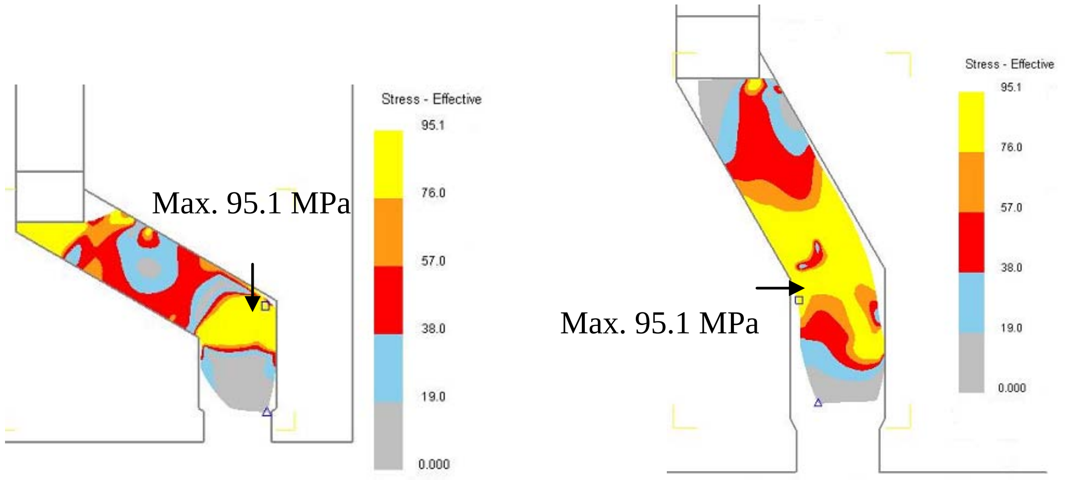
Conclusions

This study has employed DEFORM™ 2D FE code to investigate the plastic deformation behavior of CuZn37 brass alloy during one- and two-turn CCA extrusion processing. The simulations have focused specifically on the effects of the processing conditions on the effective strain, the rotation angle and the effective stress induced within the extruded workpiece. In general, the numerical results have shown that:

(1) The effective strain within the extruded CuZn37 brass alloy billet is maximized by performing one-turn CCA extrusion with an orientation angle of ϕ=90 and a friction factor of m=0.6.

(2) The rotation angle induced in the extruded billet during one-turn CCA extrusion reduces as the orientation angle increases. In one-turn CCA extrusion processing with a channel orientation angle of ϕ=90^o, the maximum rotation angle occurs in the upper region of the billet as it passes the turn in the die and extrudes toward the die exit. By contrast, in one-turn CCA extrusion with a channel orientation angle of ϕ=135^o, the maximum rotation angle is located in the lower region of the billet as it exits the die.

(3) In two-turn CCA extrusion processing, the effective stress induced in the billet reduces as the billet passes around the second turn in the die set. Consequently, the tensile stress is reduced and the hydrostatic pressure is increased. The magnitude of the maximum effective stress is independent of the channel orientation angle.



(a) ϕ=120^o, m=0.2, two turn (b) ϕ=150^o, m=0.2, two turn

Fig. 5 Distribution of effective stress in CuZn37 brass alloy following two-turn CCA extrusion processing

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