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ORIGINAL ARTICLE

Numerical simulation of Al1070 alloy through hybrid SPD process

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Abstract Material processed through severe plastic deformation (SPD) achieved ultra large plastic strain with improved mechanical properties at minimum cost as compared to other methods. Among all SPD method, equal channel angular pressing (ECAP) produces defect-free ultra large plastic strain without changing initial dimension of the sample, when pressed through two intersecting channels. In the present work, a hybrid SPD process (ECAP-based extrusion) is used for plastic deformation of Al1070 alloy billet, and the results (equivalent stress, effective plastic strain and punch load) are compared with conventional ECAP-based technique. The effect of corner radius (outer radius, inner radius) and extrusion die angle on the deformation behaviour i.e. effective plastic strain, equivalent stress and load at die wall has been studied using finite element method. It is observed that extrusion die angle has negligible influence on equivalent stress, whereas equivalent stress decreases with increase in outer radius. Effect of coefficient of friction is also noticed on the flow behaviour of billet.

Keywords Al1070 alloy · Severe plastic deformation · ECAP · Hybrid SPD · Finite element method · Friction

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1 Introduction

With increase in demand of high strength material for today's industries, researcher motivated to do lot of modification on their technique to set for better mechanical properties like strength, strain, grain refinement, surface finishing, fatigue life and cost of product. This is possible by casting of alloying element through expensive casting techniques [1]. Non-conventional processes other than casting are also used for grain refinement such as powder metallurgy, heat treatment, casting through quenching, phase change method, electro deposition process and vaporization method. These methods enable to achieve large strain in the material but it needs a secondary or tertiary process to resize and reshape the product geometry causing it more expensive. Conventional deformation techniques such as extrusion, forging, and drawing plastically deform the material, but are unable to produce ultra-fine grain (UFG). In order to achieve large plastic strain at minimum cost, SPD method has been used recently by many authors [2–5]. Several SPD methods used for ultra large plastic strain of the material are accumulative roll bending (ARB) [6, 7], high pressure torsion (HPT) [8], cyclic extrusion compression (CEC) [9], repetitive corrugation straightening (RCS) [10] ECAP [2, 11–14]. Billet deformed through ECAP has high length to weight ratio, improved fatigue strength and good mechanical properties as compared to other SPD methods [15].

UFG achieved through ECAP uses a different route of rotation (A, B_A, B_C and C) of sample before pressing through two intersecting channels. Each route of rotation has its individual significance and their use depends upon the user requirement [16]. Billet passed through route C (rotated by 180° angle either clockwise or anticlockwise) imparts a considerable rotation to grain and sub grain, resulting in strong texture and improved mechanical properties as observed by Segal (1995) [2]. He has also noticed higher strain hardening through route A as compared to that through route C. Sample with 1-mm void is deformed through a 135° channel angle resulting in maximum stress inside the void, but deformation load reduces to 30% as compared to that of void-free billet [3]. Investigator carried grain refinement of high strength alloy (Al 6063) through two-turn ECAP and found that the number of passes decreases with increasing billet temperature to achieve fine and homogenous grain [4].

Numbers of experiment done by several authors suggest that 90° ECAP channel angle with approximately 20° corner angle produces large plastic strain as compared to the other channel angle [5, 11]. Investigators obtained a maximum effective plastic strain of 1.15 mm/mm in the billet when passed through 90° channel angle and 0° corner angle, which increases with an increase in the number of passes [2, 17]. To get a high strength product with reduced processing time and wastage of material, a multi-bend channel is developed by authors to achieve required effective plastic strain in a single press [18, 19]. The work presented on copper alloy shows that strain uniformity increases with decreasing channel angle (120 to 100°) at the constant corner radius of 1 mm [18]. The authors observed that hardness of material increases up to two turns and remains constant thereafter during plastic deformation of pure aluminium [19]. They also found that mis-orientation angle increases with increase in the number of turns as observed through the microstructure.

The author found that doubling of effective plastic strain in a single press of pure aluminium is possible with two-turn (S-shape) ECAP channel [20]. They observed non uniform strain throughout the sample when channel offset decreases from 15 to 10 mm. Authors have used upper-bound method during deformation of billet through ECAP process and found that deformation load as well as effective plastic strain reduces with increase in corner angle [5, 21]. Alkorta and Sevillano have studied the effect of pressure needed for frictionless ECAP of perfectly plastic and strain-hardening materials using an upper-bound analysis and finite element method (FEM) [22]. They observed that heterogeneity of plastic strain across the sample thickness is reduced with the help of back pressure.

The present paper aims towards new die design to achieve ultra large plastic strain at minimum effort. Similarly, the authors have also used a hybrid approach combining ECAP and extrusion process into a single die to understand the deformation behaviour (effective plastic strain, equivalent stress and load at die wall) through simulation of an Al1070 alloy billet when pressed through hybrid SPD process. Hybrid SPD process is more effective because of the following: (a) chance of surface failure is more in case of ECAP as compared to that of hybrid SPD due to unavailability of back pressure, (b) it achieves longer ECAPed billet in a single press, and (c) it achieves higher effective plastic strain and equivalent stress as compared to those of ECAP process.

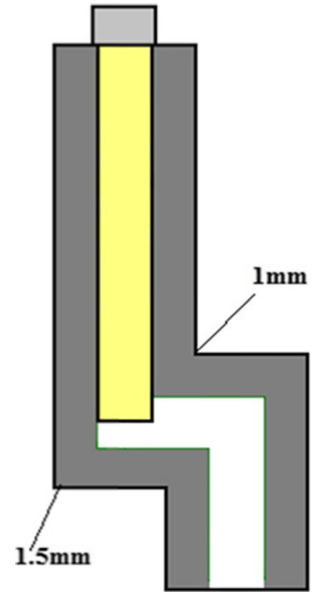


Fig. 1 Schematic of two-turn ECAP die

2 Method of die design

In a two-turn ECAP, square billets are used through two intersecting channels having channel angle of 90° and corner angle of 10° with inner corner radius of 1 mm and outer corner radius of 1.5 mm, respectively as shown in Fig. 1. Bottom die

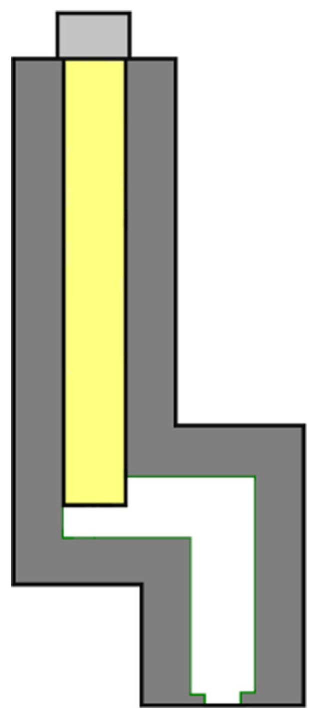


Fig. 2 Schematic of hybrid SPD die at 90° extrusion die angle

Table 1 Properties of sample and tool materials

Name of materials	Young's modulus	Poisson's ratio
Al1070 (99% Al)	6.8900000E + 004	3.3000000E−001
Die-punch (tool)	Rigid material	

channel has square cross section of 8 × 8 mm^2. Inlet and exit channel are offset by 16 mm and set at 90° channel angle. Length of the inlet and outlet channel is 56- and 40-mm long. Billet is pressed through the die inlet channel by using rigid body punch, which comes from die exit channel. In the present method, billet passed through two-turn ECAP is used to follow route C rotation to achieve double pass in a single press with minimum wastage of material. For hybrid SPD process, dies are further redesigned where exit channel lengths of ECAP die reduced from 40 to 25 mm. Extrusion dies having a 4-mm cylindrical die opening are inbuilt in exit channel of the ECAP die as shown in Fig. 2. Extrusion die angles are designed at 30°, 45°, 60°, 75° and 90°.

3 Finite element-based simulation

A commercial FEM-based Deform-3D version 10.1 software was used for simulation of elastic/plastic material in two-turn ECAP and hybrid SPD process to find the effective plastic strain, equivalent stress and load on billet as well as die. Billet used for present simulation is a commercial Al1070 alloy, which is modelled as elastic-plastic, isotropic, Huber/Mises material with properties listed in Table 1. Work hardening law is followed by Swift's model as given in Eq. (1) [23]. Tetrahedron mesh with size of 0.3 mm at a constant size ratio without re-meshing is used for simulating the flow behaviour. Mesh size of 0.15 to 1 mm has been tested and found that 0.3-mm mesh size provides the least compromise variation of properties and simulation time. Plastic deformation is done at punch speed of 1 mm/s. Coefficient of friction (0.05) is an ideal condition for present simulation, which is difficult to achieve but may be possible by using graphite coating with mirror surface finishing of die channel and billet during experimental work. However, in order to look for reality condition of frictional coefficient, different values of coefficient of friction (0.1, 0.2 and 0.3) have been used in the present simulation to observe the effective plastic strain, equivalent stress, contact surface and punch load.

$$\sigma = 159(0.02 + \varepsilon)^{0.27}, \quad (1)$$

where σ is flow stress and ε is plastic strain.

4 Results and discussion

Deformation behaviour of high purity aluminium billet through ECAP and hybrid SPD process has been analysed and discussed in the subsequent sections. Selection of softer material (Al1070 alloy) has been done to avoid the flow unstability and shear localization behaviour. This paper shows evolution of the billet's mechanical properties (flow behaviour, effective plastic strain, equivalent stress, load on die and billet) when passed through route C rotation. This paper discusses about the shearing phenomenon across the billet with and without back pressure when it passed through numbers of die turns.

4.1 Mesh deformation

Billet pressed through ECAP channel gives information about sheared plane area in term of sheared mesh deformation as shown in Fig. 3. Shear plane in each turn changes with changing die channel angle. The following observations have been made during simulation through ECAP channel.

Die sharpness is imposing large plastic strain at die wall corner, thus induces more stress as compared to mesh near offset channel centre. Thus, stressed element tries to move towards the top of the die for relieving of stress, and hence,

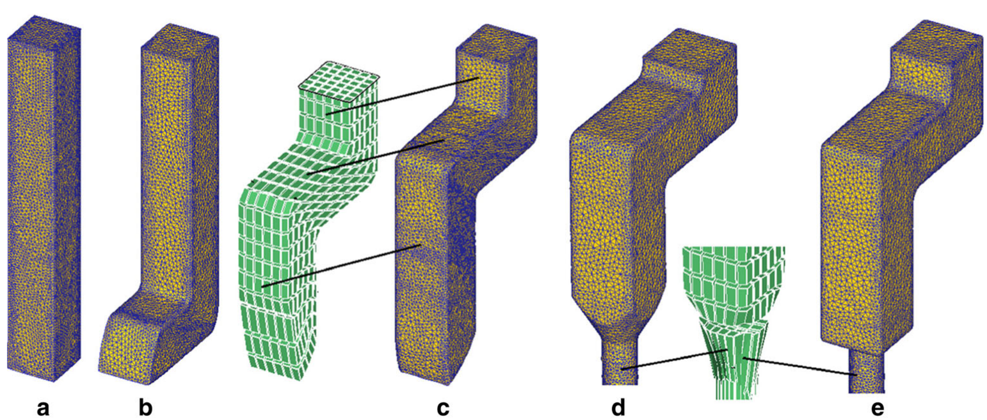


Fig. 3 Sheared mesh in two-turn ECAP (**a**–**c**) and hybrid SPD process (**d**–**e**)

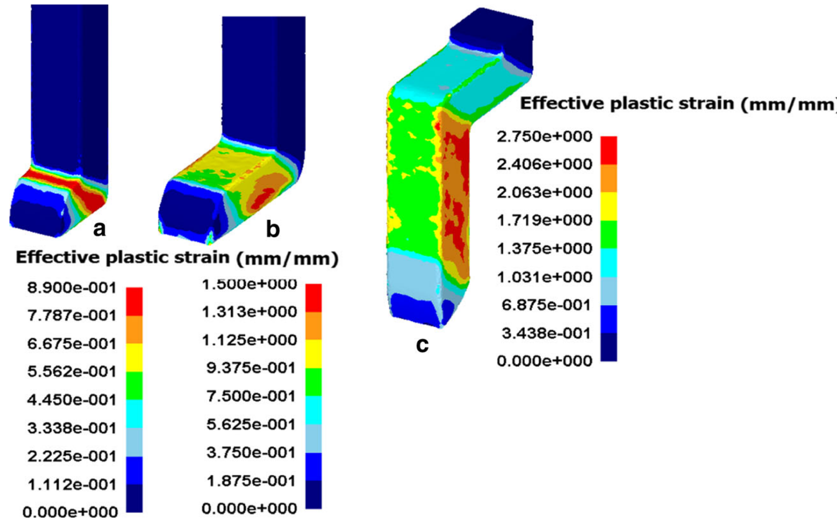


Fig. 4 Evaluation of effective plastic strain in two-turn ECAP

density on top of the die increases. When billet enters into the second turn of the channel and towards the exit of dies, it is observed that mesh size, orientation and its distribution at the entrance and in second turn are the same. Mesh orientation as well as shape at the entrance and in second turn remain the same because meshes are allowed route C rotation. Similarly, mesh distribution throughout the channel is aligned towards load direction. When billet enters into the extrusion channel through ECAP dies, mesh element broke into smaller sizes, and hence, more refinement is observed. It is also observed that mesh elements are elongated along extrusion direction. Green colour prismatic element shown in Fig. 3 is used to observe the flow analysis of deformed surfaces of the billet. The process of doing this is known as gridding.

4.2 Effective plastic strain

Distribution of effective plastic strain in the ECAPed billet is shown in Fig. 4. Effective plastic strain in each turn changes with changing die channel angle. The following observations have been made during simulation through ECAP channel.

Throughout the deformation zone, it has been observed that the portion of the tip of the billet is not shear deformed. Minor strain developed at the tip of the billet is due to compression. Rest part of the billet continues to deform until it exits from the channel. When the billet enters into offset zone and consequently into the second turn of the channel, it passes through a number of sharp corner edge resulting in higher shearing strain. Hence, effective plastic strains of 1.5 and 2.75 mm/mm were obtained at lower part of the billet in the offset zone and second turn of die, respectively.

In order to understand the variation of effective plastic strain at fixed point of channel, five random points at different sections of channel are taken as shown in Fig. 5. Figure 6 shows effective plastic strain of the random points selected on the billet with stroke length. Point P1 is selected near tip of the billet, which partially sheared when passed through corner of the die channel and remained constant throughout the length of the die channel. Point P2 is taken at a distance from P1, which goes through most shearing action resulting in higher effective plastic strain as compared to other point taken on the billet. Similar shearing action has been observed for points P3 and P4, which indicates that these points are less sheared as compared to point P2. It has been observed that point P5 never goes for shearing action and remains undeformed until given stroke length.

Distribution of effective plastic strain in hybrid SPD process at two different extrusion die angles (45° and 90°) is shown in Figs. 7 and 8. The following observations have been made during simulation through hybrid SPD process.

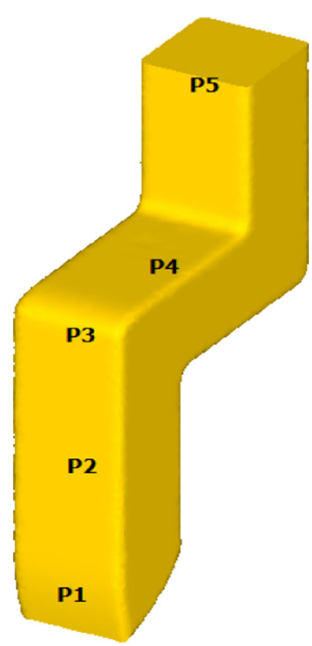


Fig. 5 Random points selected in two-turn ECAPed billet

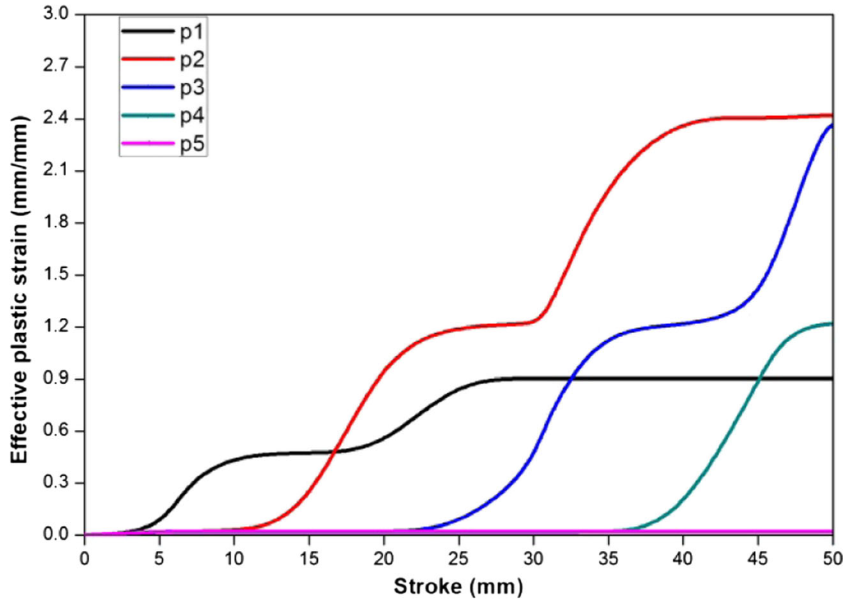


Fig. 6 Flow of effective plastic strain across selected points

Like ECAP process, planes of the billet under given load continue to orient resulting shearing action inside channel, offset channel and exit channel of the die resulting in improvement in mechanical properties (Young's modulus, shear strength, shear strain, hardness, surface roughness). But with addition to this, billet entering into the extrusion channel of the die, its plane is elongated along loading direction instead of orientation resulting in higher extensional strain, thus increases the mechanical properties (tensile stress, longitudinal strain, ductility, plasticity). Throughout the deformation zone, it could also be observed that non sheared tip of the ECAP billets is deformed at the inlet of extrusion channel. Raise of effective plastic strain at the tip of the ECAP billet is due to redundant deformation and compression of the billet along the extrusion direction. With increase in die angle, dead zone increases resulting in more friction due to which shearing action enhanced, and hence, effective plastic strain increases. After exit from the extrusion die, back pressure increases continuously along the stroke length, resulting increase in effective plastic strain throughout the length of the billet in ECAPed zone. An increase in effective plastic strain in offset channel is because of more shearing action applied due to

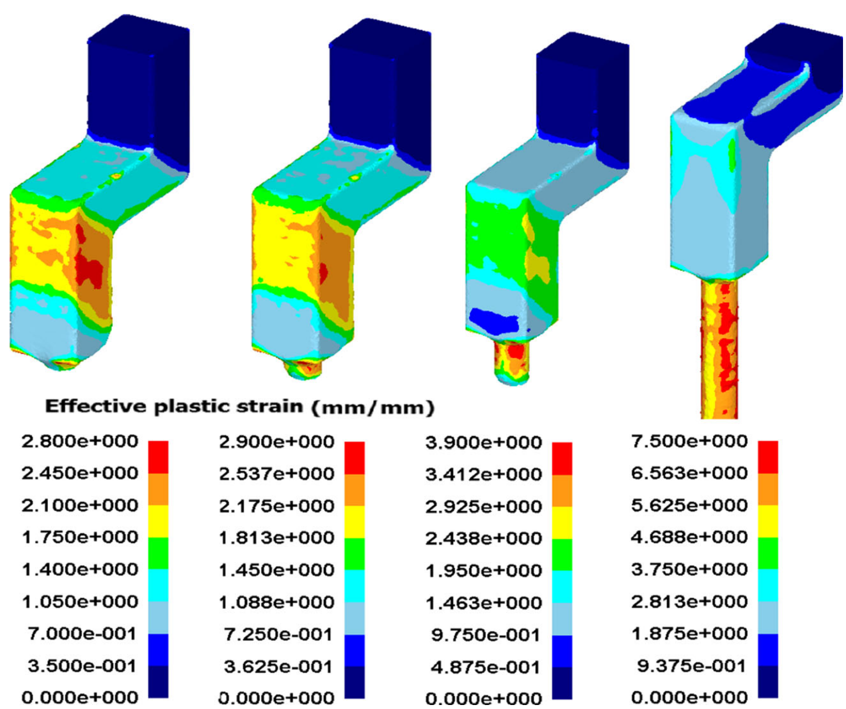


Fig. 7 Billet effective plastic strain in hybrid SPD process channel at 45° extrusion die angle

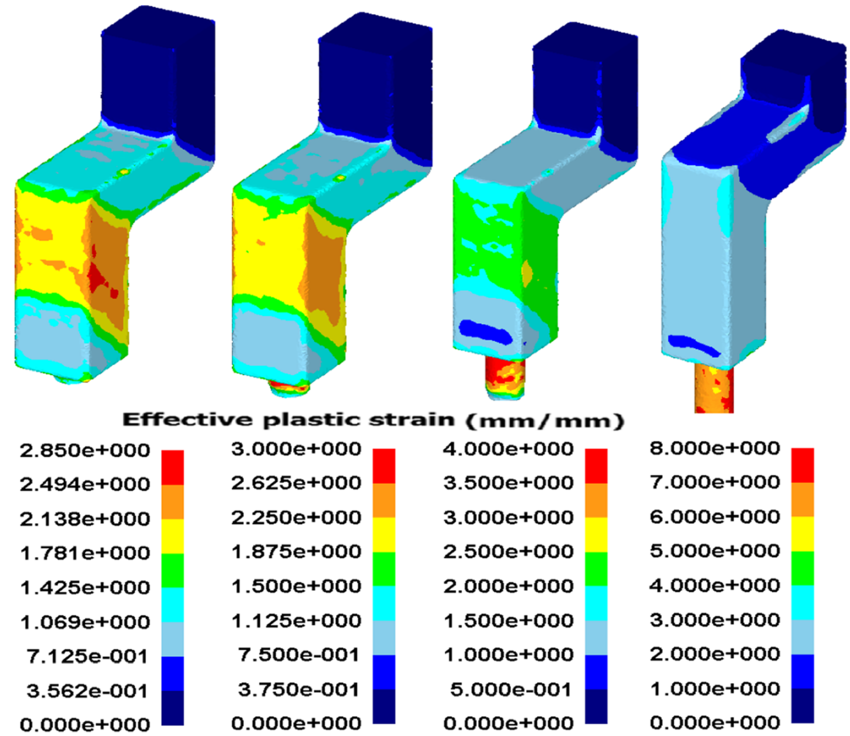


Fig. 8 Billet effective plastic strain in hybrid SPD process channel at 90° extrusion die angle

back pressure, whereas an increase in effective plastic strain in exit channel is because of compression applied due to back pressure. In the extruded billet, effective plastic strain around the surface is more uniform for a lower die angle as compared to that for a higher die angle. This happened due to less redundant deformation. It was observed from Figs. 7 and 8 that effective plastic strains in extruded regions of the lower die angle is 7.50 mm/mm and for higher die angle is 8.00 mm/mm at coefficient of friction 0.05.

To understand the variation of effective plastic strain, three random points on the billet are selected in such a way that after extrusion, it will lie in the extrusion die, at the inlet and exit of the channel as shown in Fig. 9. Figure 10 shows effective plastic strain of the billet with increasing stroke length. It has been observed that with increasing stroke length, billet continuously deforms at offset channel, exit channel and

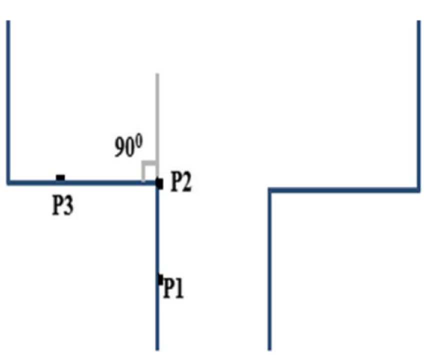


Fig. 9 Position of selected point in different sections of hybrid SPD process

extrusion channel. As a selected point, P1 is taken after extrusion resulting in more deformation as compared to P2 and P3; thus, it induces higher effective plastic strain for a given stroke length.

Throughout the deformation, it is observed that effective plastic strain increases with increasing extrusion die angle from 30° to 90°. Minimum effective plastic strain is possible at the lower extrusion die angle (30°) while its flow pattern in the lower and higher extrusion die angles is the same even for varying coefficients of friction as shown in Fig. 10. Varying coefficients of friction and increasing extrusion die angle increase the amount of dead zone material resulting in increase in effective plastic strain. During extrusion, material accumulated in dead zone area slipped because of continuous increase in punch pressure due to which its properties vary with increase in the extrusion die angle. Slipping of dead zone material is a cause for lower effective strain at 60° extrusion die angle as compare to that at 45° extrusion die angle.

4.3 Equivalent stress

Distribution of equivalent stress in the ECAPed billet is shown in Fig. 11**.** Equivalent stress in each turn changes with changing die channel angle. The following observations have been made during simulation through ECAP channel.

Throughout the deformation zone, it has been observed that stress developed at the tip of the billet is due to compression. The billet tip is not sheared, hence resulting in stress due to compression is very low. When the billet enters into the first

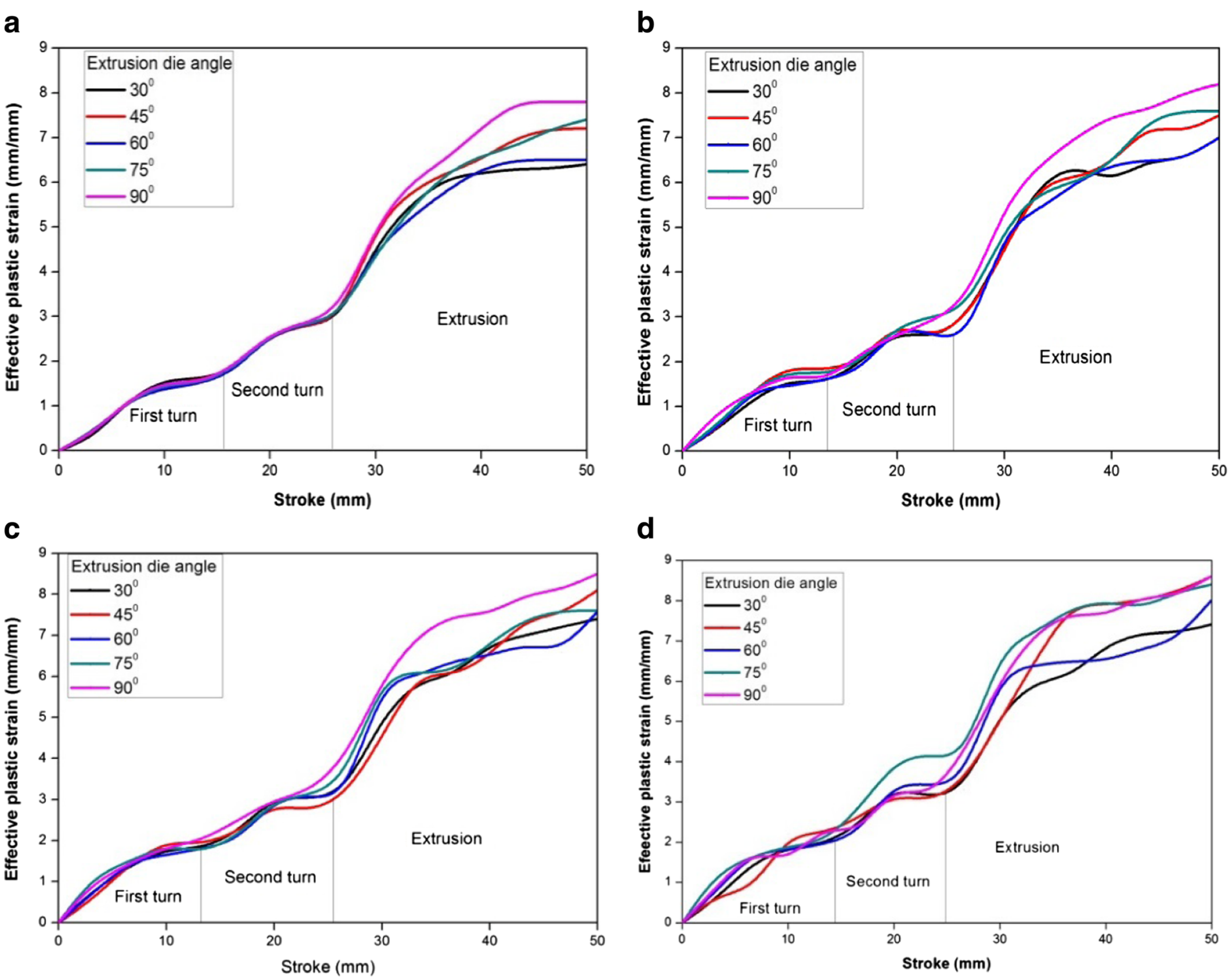
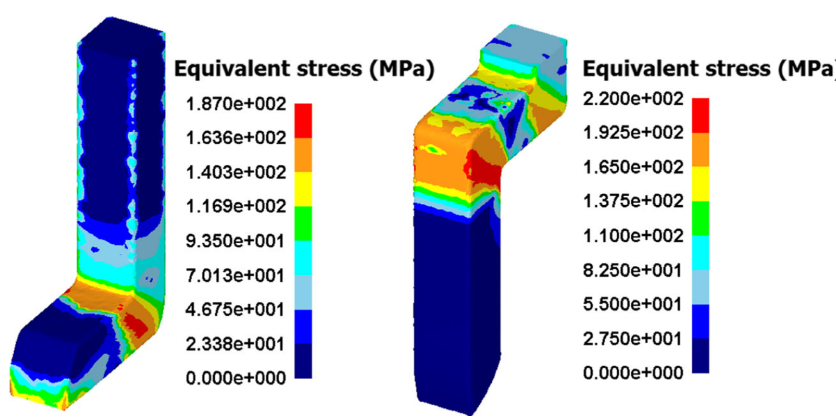


Fig. 10 Effective plastic strain in hybrid SPD processes with coefficients of friction: 0.05 (**a**), 0.1 (**b**), 0.2 (**c**) and 0.3 (**d**)

turn, into the offset zone and consequently into the second turn of the channel, planes of the billet continuously sheared resulting in higher shearing stress. Hence, in the offset zone, the bottom of the die shows equivalent stress of 187 MPa, and in the second turn of die, it shows equivalent stress of 220 MPa. In addition to this two-turn ECAP after primary yielding at the first turn, the material undergoes unloading in an end segment of the offset channel (release of stress) as shown in Fig. 11 and finally yields at the second turn, which takes place on the opposite side of yield surface in the first turn.

Fig. 11 Equivalent stress distributions in two-turn ECAP



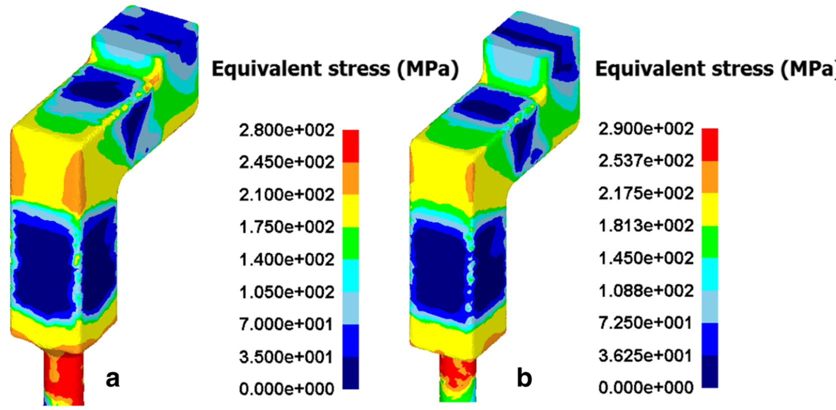


Fig. 12 Equivalent stress in two-turn hybrid SPD process at 45° (**a**) and 90° (**b**) extrusion die angles

Distribution of equivalent stress in hybrid SPD process at two different extrusion die angles (45° and 90°) is shown in Fig. 12. The following observations have been made during simulation through hybrid SPD process.

The stresses are released in the middle segment of the billet as well as in the second turn of the exit channel. Stress developed in case of hybrid SPD processes is higher as compared to that of two-turn ECAP processes. This happened due to presence of extrusion die, which imparts back pressure. Maximum stress developed in the second turn of hybrid SPD process at 45° extrusion die angle is 240 MPa whereas at same section, maximum stress developed by ECAP processes is 220 MPa. Very little variation of stress was observed with the change in extrusion die angle. Due to low coefficient of friction (0.05), slipping was predominant

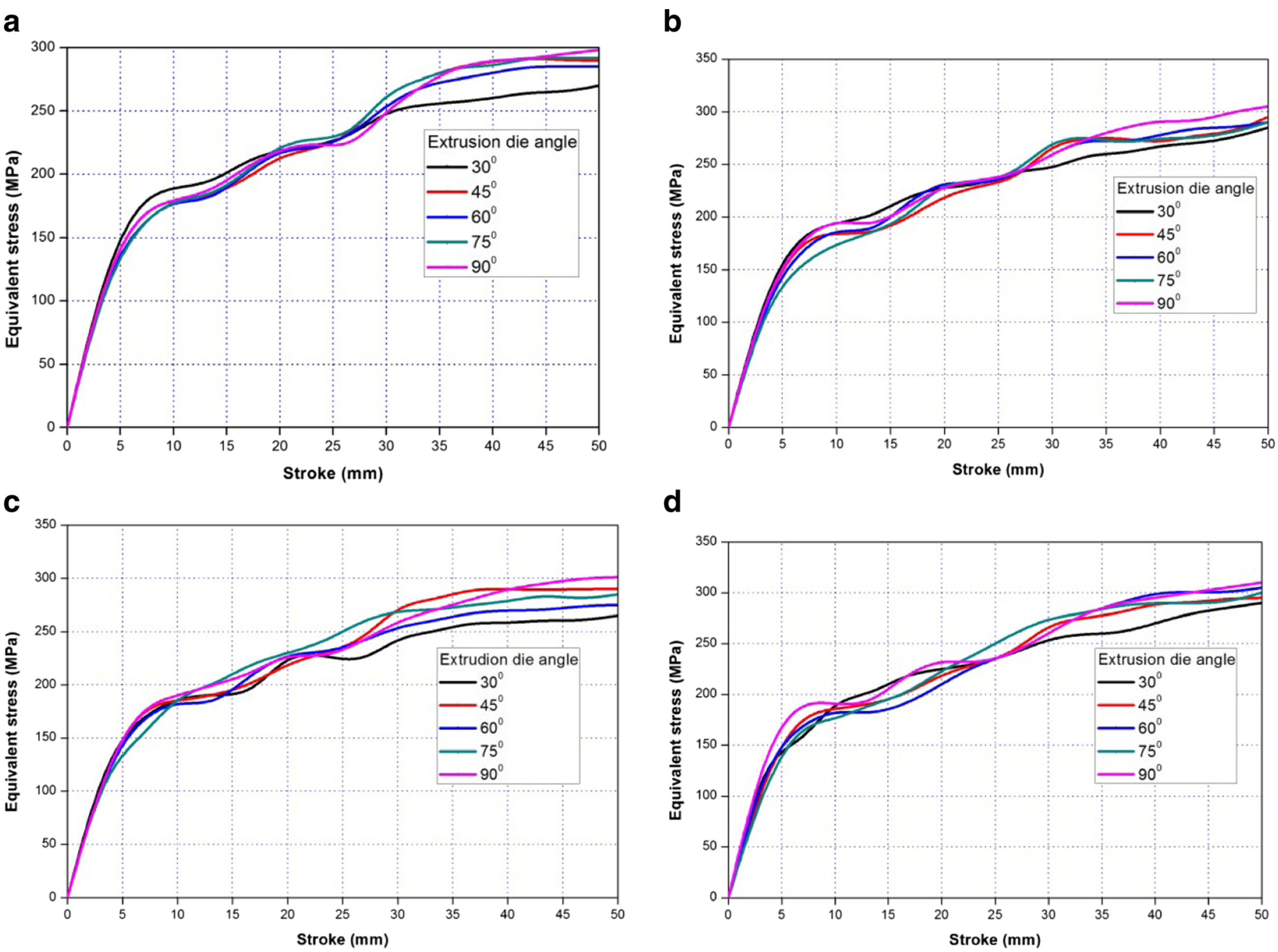


Fig. 13 Equivalent stress in hybrid SPD processes with friction coefficients 0.05 (**a**), 0.1 (**b**), 0.2 (**c**) and 0.3 (**d**)

over shearing, resulting in insignificant variation of stress for both the extrusion die angles.

Due to increase in effective plastic strain, material became strain-hardened resulting in increase in equivalent stress. Maximum equivalent stress achieved at 90°, which decreases with decrease in the extrusion die angle as shown in Fig. 13. Equivalent stress is proportional to rise in coefficient of friction for a constant extrusion die angle because its back pressure increases. Increasing the extrusion die angle and coefficient of friction is a cause for plane slipping in dead zone region due to which mechanical properties of billet vary.

4.4 Contact surface

Contact surface between the billet and die wall plays important role in determining the coefficient of friction and deformation load. It is observed from Fig. 14 that contact surface is higher in case of 90° extrusion die angle resulting in higher back pressure, due to which deformation load increases. Contact surface increases with increase in coefficient of friction and extrusion die angle. Increase in contact surface area between the billet and die channel needs more punch load to cross the die opening. Contact surface area of the all extrusion die angles is almost equal at higher frictional coefficient of 0.3.

4.5 Loading condition

The billet undergoes deformation through ECAP and hybrid SPD process; hence, load on billet as well as on die are shown in Figs. 15 and 16. The following observations have been made during simulation through ECAP channel.

At the inlet channel, in the first turn and in the second turn, the load required to compress the billet sharply increases with stroke length for both the ECAP and hybrid SPD process, but when the billet passes through the offset channel, exit channel and extrusion exit channel, load gradually increases due to shearing of planes as shown in Fig. 15. Maximum 20 KN load is experienced by the billet at frictional coefficient of 0.3 to cross the 90° extrusion die angle. Magnitude of load experience by the bottom die is higher as compared to

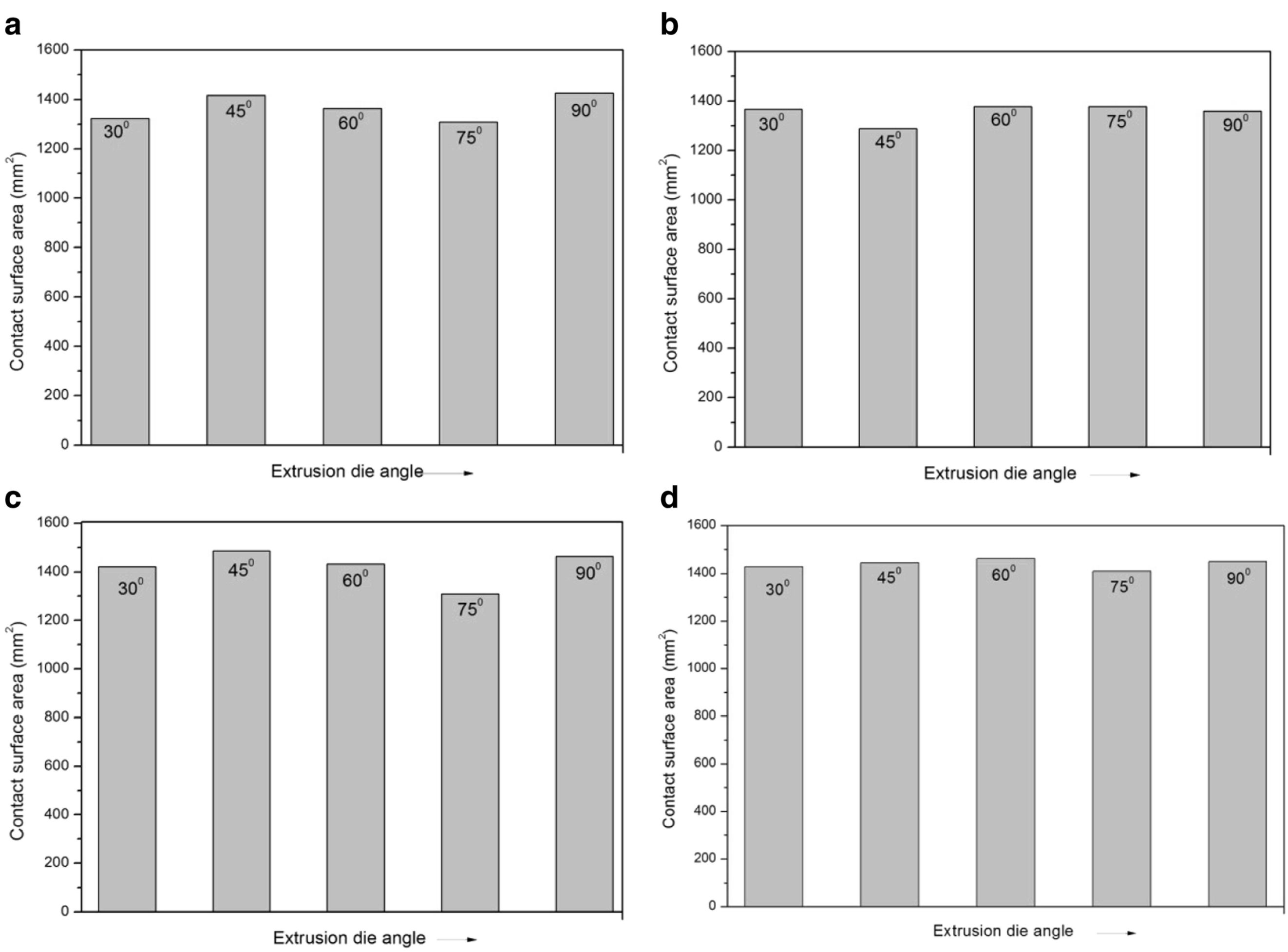


Fig. 14 Contact surface in hybrid SPD process at coefficients of friction: 0.05 (**a**), 0.1 (**b**), 0.2 (**c**) and 0.3 (**d**)

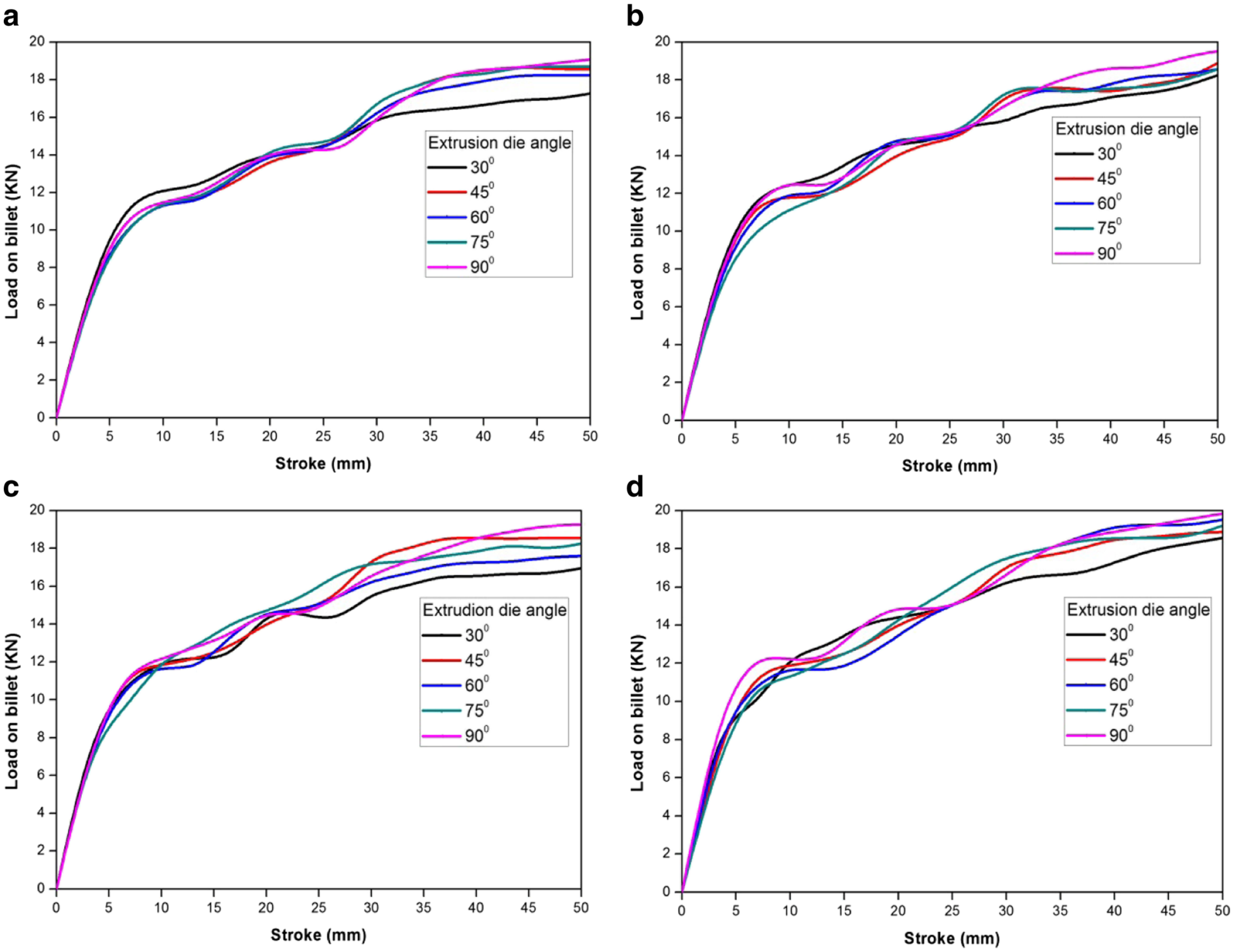


Fig. 15 Load experienced on the billet at coefficients of friction: 0.05 (**a**), 0.1 (**b**), 0.2 (**c**) and 0.3 (**d**)

load on the billet. This may be due to the gradual increase in contact area along stroke length. The billet undergoes unloading in the offset channel as well as in the exit channel, which can be seen from Fig. 16. In each turn of ECAP die, requirement of load increases when coefficient of friction increases from 0.05 to 0.3. Material accumulated in dead zone area of 90° die angle is maximum compared to that of the other extrusion die angles; this is because of more effective plastic strain causing material to stick to the dead zone area rather than slipping. To achieve the slipping action of material in the dead zone area, higher punch load is needed. Material accumulated in dead zone area of 30° die angle is minimum compared to that of the other extrusion die angles; this is because of lower effective plastic strain causing material to slip faster. Similarly, accumulation of material in dead zone area of 45° and 60° extrusion die angles has been observed. It is found that slipping of plane at 75° extrusion die angle is very fast at frictional coefficient of 0.2 and 0.3; thus, it reduces the punch load as compared to that at the other extrusion die angle, which is shown in Fig. 16c, d.

5 Conclusions

This paper concluded with hybrid process concept of SPD method and compared the conventional ECAP with hybrid SPD process. The authors find through simulation that the proposed hybrid process gives ultra large plastic strain along with improved mechanical properties and product shape as desired. The following are the generalized conclusions derived through simulation.

Hybrid SPD processes

- Higher elemental density in the offset zone is observed on top part of the billet.
- Element orientation and its distribution at entrance and in exit channel of die are the same.

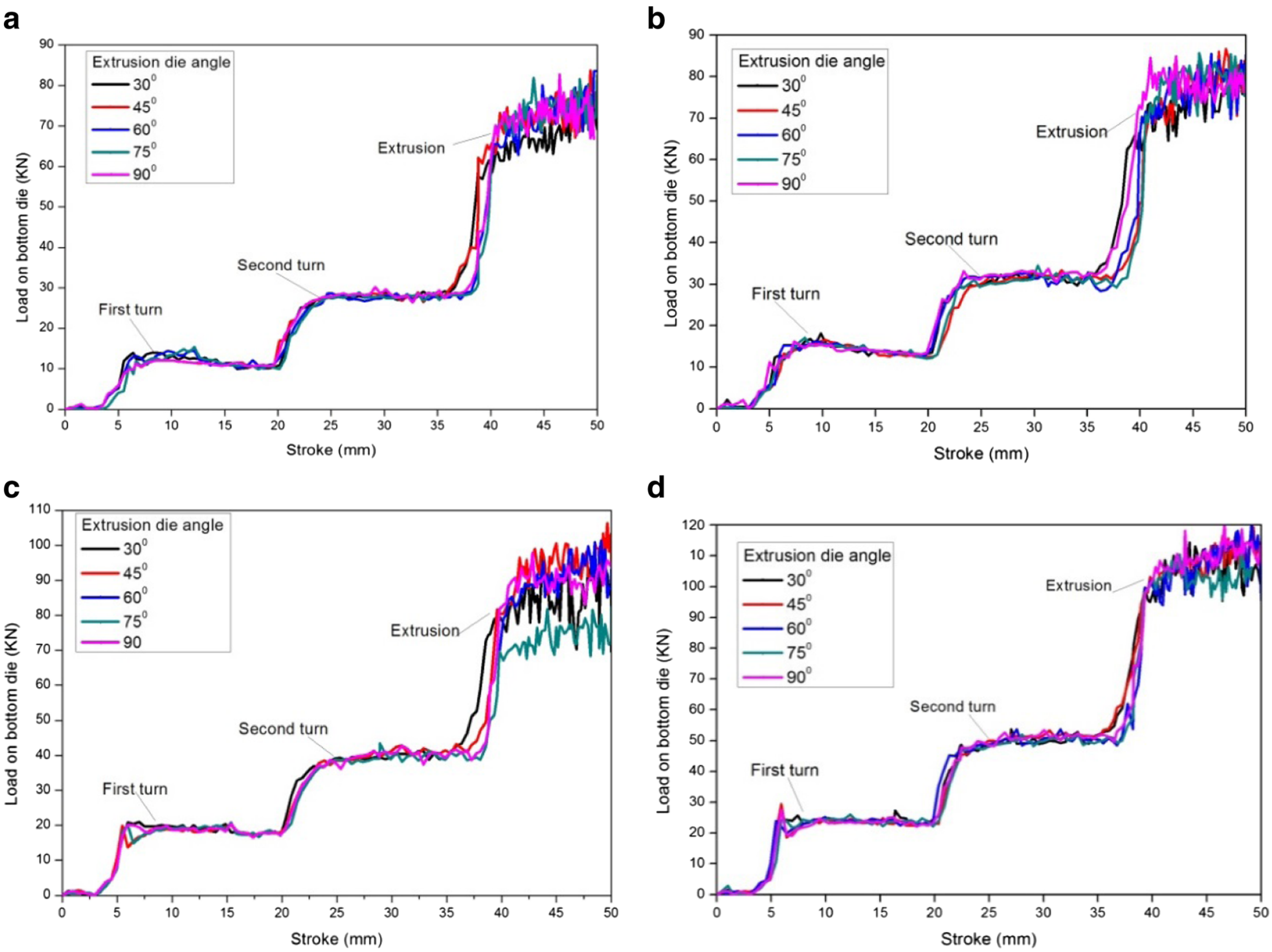


Fig. 16 Load experienced on the bottom die at coefficients of friction: 0.05 (**a**), 0.1 (**b**), 0.2 (**c**) and 0.3 (**d**)

- Equivalent stress developed at die wall corner is higher than that at die offset channel.
- Compressed tip of the billet has low effective plastic strain and stress as compare to other sheared part.
- Maximum equivalent stress and maximum effective plastic strain are observed on lower part of the billet in the offset zone.
- Effective plastic strain of the ECAPed billet further increases when the billet enters into the extrusion die.
- Distribution of effective plastic strain around the deformed surface is more uniform for a lower die angle as compared to that for a higher die angle.
- Effective plastic strain increases with increasing coefficient of friction.
- Equivalent stresses of the billet are released in the middle segment of the offset channel, and similar observation is also seen in the exit channel.
- Stresses developed in case of hybrid SPD processes are higher as compare to those of ECAP processes.
- At inlet channel, the first turn and second turn amount of load required to compress the billet sharply increases but when the billet enters into the offset channel, exit channel and extrusion channel, the billet load gradually increases.
- Contact surface increases with increasing extrusion die angle and coefficient of friction resulting in higher deformation load.
- Bottom die experienced higher load as compare to load required for billet deformation.
- Slipping of plane at 75° extrusion die angle is very fast at frictional coefficients of 0.2 and 0.3; thus, it reduces the punch load as compared to that at the other extrusion die angle

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