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Deformation behaviour of commercial pure copper during repetitive upsetting-extrusion (RUE) using a modified die design

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Abstract

Repetitive upsetting-extrusion (RUE) process which was originally invented for bulk mechanical alloying is currently being used to process bulk materials. Bulk materials are subjected to severe plastic deformation (SPD) using the same die design that was used to process powder materials. A more recent study on the RUE process has revealed that the current die design is not appropriate for processing bulk materials as it imparts defects such as axial hole or funnel during extrusion and folds or laps during the upsetting stage of successive RUE cycles. A modified RUE die design is proposed in this work to avoid these defects. Deformation behaviour of a bulk commercial pure copper during RUE using the modified die design has been evaluated using finite element analysis (FEA). Actual RUE experiments on commercial pure copper have also been carried out to validate the FEA results. Results obtained indicate that the modified die design can be successfully used to subject bulk materials to large number of RUE cycles.

Key words: upsetting, extrusion, RUE, SPD, copper

1. Introduction

Among the various bulk severe plastic deformation processes [1–5] that are in vogue, repetitive upsetting-extrusion (RUE) is a relatively new process. The process was originally invented by Aizawa et al. [6] to process powder materials for bulk mechanical alloying. Hu Lianxi et al. [7] used the RUE process to deform a bulk aluminium alloy and established that the process was capable of refining grain size to submicron level. A more detailed study on the deformation behaviour of bulk commercial pure copper (CP Cu) during RUE process by Anjali et al. [8] and Balasundar et al. [9] has revealed that the process not only imparts inhomogeneous deformation but also results in defects such as folds or laps during the upsetting stage and axial hole or funnel during the extrusion stage of successive RUE cycles. Balasundar and Raghu [10] through numerical analysis and experiments established that the formation of the defects can be attributed to the current RUE die design. In this work, based on the extrusion defect (axial hole or funnel) analysis carried out by Balasundar and Raghu [11], a modified die design for processing bulk materials is being proposed. The deformation behaviour of bulk commercial pure copper subjected up to 4 RUE cycles in the modified die design has been evaluated in terms of deformation pattern, strain distribution and deformation homogeneity using a commercial finite element analysis software MSc.Marc2010r1. RUE experiments on bulk CP Cu have been carried to validate the FEA results. The results obtained from the numerical analysis and experiments on CP Cu are presented and discussed here.

2. RUE process

A typical RUE cycle consists of two basic stages (1) upsetting and (2) extrusion as shown in Fig. 1. A cylindrical work piece of known dimension is first subjected to upsetting, wherein the length is reduced and the cross-sectional area is increased. The upsetted work piece is subsequently subjected to extrusion,

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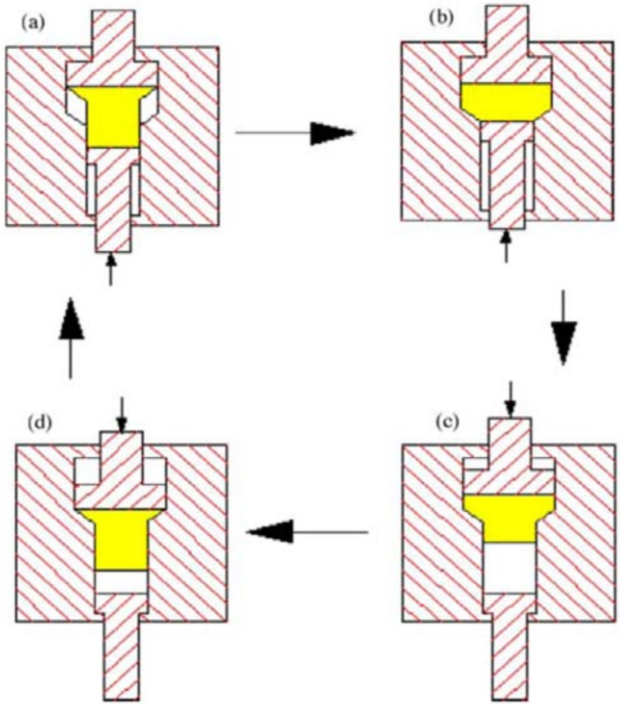

Fig. 1. Typical RUE cycle [7].

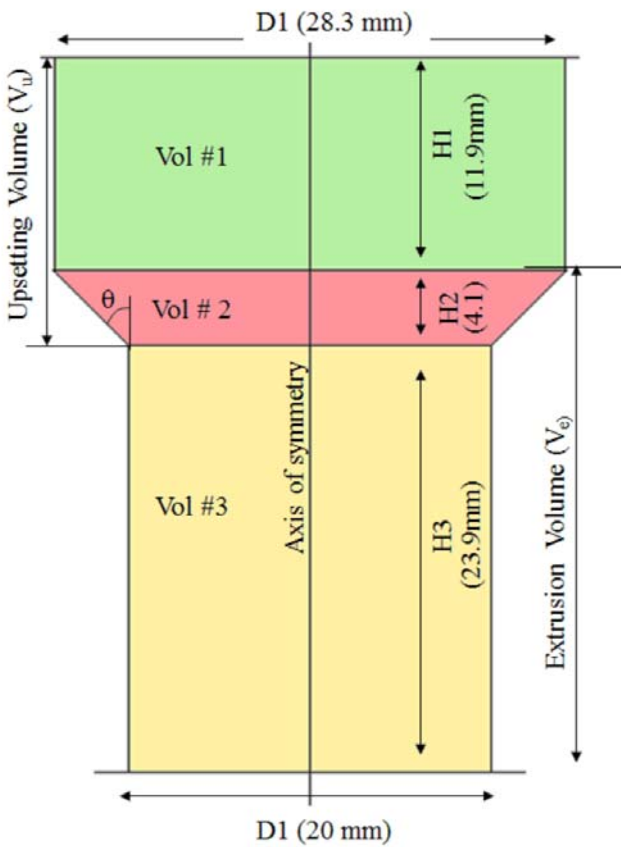

Fig. 2. Original RUE die design.

wherein the length is increased and the cross-sectional area is reduced. The upsetting and extrusion processes are repeated over and over again till the desired number of cycles is reached. During upsetting, the material deforms perpendicular to the upsetting direction whereas during extrusion the material deforms parallel to the upsetting or extrusion direction. This reversal of flow during a RUE cycle causes grain refinement [7].

3. Original die design and the deformation behaviour bulk CP Cu

The RUE die design that is being currently used to process both the powder and bulk materials [6–10] is shown in Fig. 2. It can be divided into three regions each having a volume vol#1, vol#2, and vol#3, respectively. These volumes are designed in such a way that vol#1 + vol#2 = vol#2 + vol#3. During the upsetting stage the work piece fills the volume V_u = vol#1 + vol#2 and during the extrusion stage it fills the volume V_e = vol#2 + vol#3. The volume of the work piece (V_w) therefore is given by V_w = vol#1 + vol#2 = vol#2 + vol#3. Current RUE dies are designed in such a way to keep the volume of the middle region, i.e., vol#2 to a minimum in order to ensure that major portion of the work piece or the material is subjected to either upsetting or extrusion. The dimensions of the die and work piece that have been used by researchers [7–10] are also shown in Fig. 2. The RUE die imparts an axial true strain of $\varepsilon = 2\ \ln(D_1/D_3) = 0.693$ either during an upsetting or extrusion operation. The total axial strain and total equivalent von Mises strain at the end of an RUE cycle therefore equal to 1.386 and 1.13, respectively.

Balasundar et al. [8–10] subjected bulk CP Cu up to 4 RUE cycles and characterized the deformation behaviour by evaluating the macro- and microstructure. The macrostructure of bulk CP Cu obtained at the end of each RUE cycle is shown in Fig. 3. The presence of folds and axial hole or funnel defect can be readily observed. Balasundar and Raghu [10] through numerical analysis established that the axial hole and fold are formed during the extrusion and upsetting stages of consecutive RUE cycles. The formation of fold was attributed to the design of vol#2 (Fig. 2), which causes the initial cylindrical work piece to take a T-shaped geometry at the end of first RUE cycle [8–10]. The elbow region in the T-shaped work piece acts as a stress concentration region, thereby leading to the formation of fold during upsetting. The axial hole or funnel defect formation was also attributed to the design of vol#2 which acts as deformation zone during the extrusion process. The formation of axial hole or funnel defect causes catastrophic failure of the CP Cu work piece due to growth and coalescence of voids at the end of 4 RUE cycles. Based on the studies re-

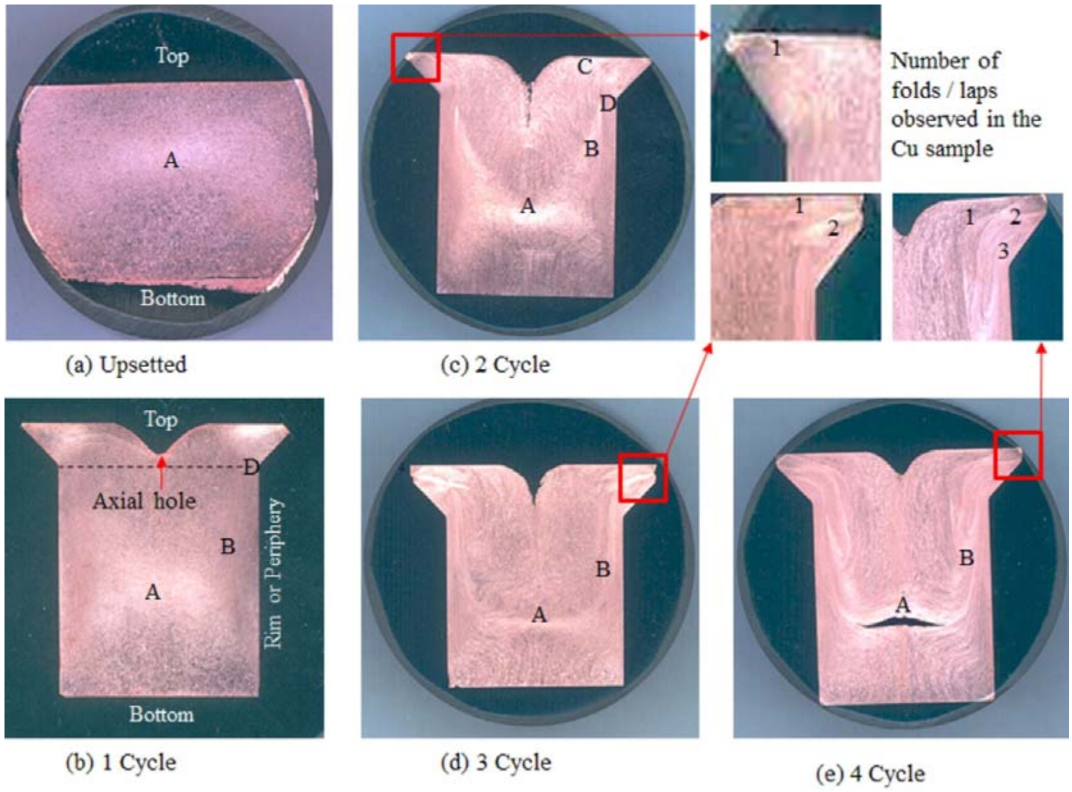

Fig. 3. Macrostructure of CP Cu subjected to increasing number of RUE cycles using the original die design.

ported [8–10], the importance of correct vol#2 design in successful processing bulk materials can readily be envisaged.

4. Modified die design

More recently, Balasundar and Raghu [11] have investigated the axial hole or funnel extrusion defect and established the conditions to avoid defect while processing a variety of engineering materials. The minimum design requirement in terms of the deformation zone height (h) and die angle (θ) to avoid the extrusion defect is

$$h \geq \frac{D_\mathrm{f}}{2}, \tag{1}$$

$$\theta \geq \tan^{-1}\left(\frac{r}{h}\right) = \tan^{-1}\left(\frac{\frac{D_\mathrm{o}-D_\mathrm{f}}{2}}{\frac{D_\mathrm{f}}{2}}\right) = \\ = \tan^{-1}\left(\frac{D_\mathrm{o}-D_\mathrm{f}}{D_\mathrm{f}}\right). \tag{2}$$

D_o and D_f are the initial diameter and final diameter of the work piece and r is the radius of the deformation zone. Fold or lap is also a common defect observed during forging process [12–14], it has also been established that the defect can be eliminated by avoiding sharp corners in the die design that cause abrupt change in the deformation pattern. Based on the available information, a modified RUE die design as shown in Fig. 4a is being proposed to process bulk materials. It can be seen from Fig. 4 that in the modified RUE die design, the height of volume vol#2 is greater than half the diameter of vol#3 as per Eq. (1). Further, to avoid the fold formation, appropriate fillets have been provided at the intersection point of two volumes.

5. Experimental procedure

5.1. *Finite element analysis*

The deformation behaviour of commercial pure copper (20 mm in diameter by 34 mm in height) during RUE using the modified die design was simulated using MScMarc2010r1. As both the shape of work piece and the nature of loading were symmetrical about an axis, an axisymmetric rigid plastic finite element model [15, 16] as shown in Fig. 4b was used for the analysis to reduce computation time. The work piece was assumed to be deformable and meshed with 4-node isoparametric axisymmetric elements. Though the initial mesh was coarse (2000 elements), during deformation the mesh was refined by automatic remeshing to accommodate large strains.

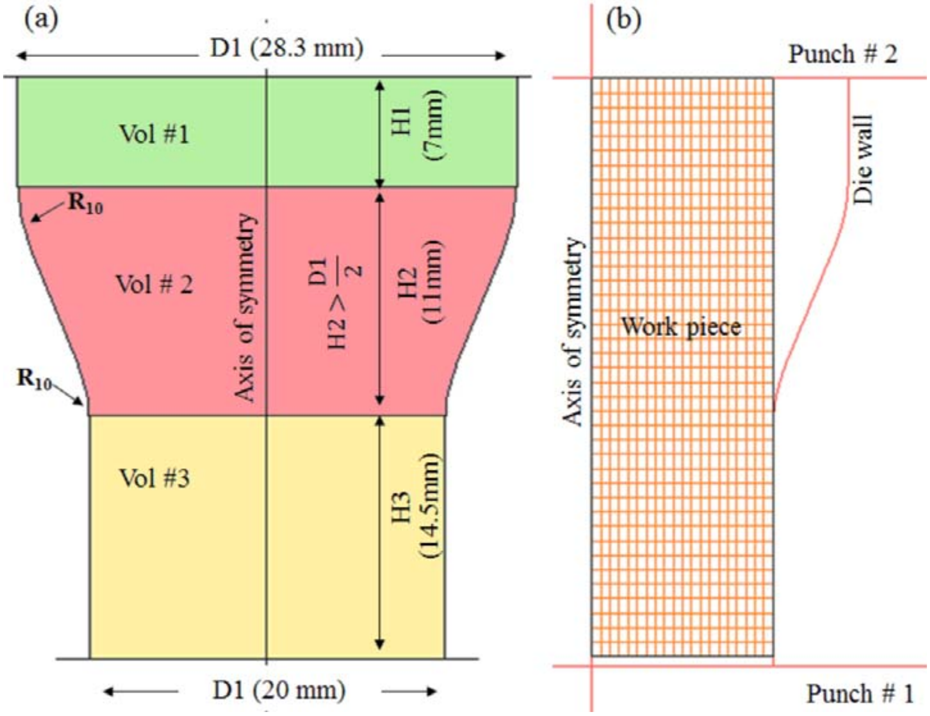

Fig. 4. (a) Modified RUE die design, (b) axisymmetric model for finite element analysis.

The number of elements was increased during the first remeshing operation and was maintained constant throughout the simulation. From the mesh sensitivity analysis, 6500 elements were found to be sufficient to model the deformation behaviour reliably. The constitutive relationship ($\sigma = 243\,\varepsilon^{0.125}$) that was established [8] by carrying our compression test on the commercial pure copper material was used to carry out the axisymmetric rigid plastic finite element analysis. The die wall, dies and punch were assumed to be rigid. For the analysis, a Coulomb friction coefficient of 0.05 was assumed between the work piece and tools.

During the upsetting stage of RUE cycle, the die wall and punch#2 were assumed to be stationary (i.e., punch#2 acts as a stationary upsetting die) by imposing zero displacement boundary conditions. Punch#1 was assigned with an upward displacement, the velocity (constant punch velocity of 1 mm s^{-1} was used for deformation) of which was controlled by using a control file that contained information on the speed, time required, number of sub-steps to be taken to achieve the specified deformation. After upsetting, punch#1 was retracted back to its original position. A constant punch velocity of 5 mm s^{-1} was used to retract the punch. During extrusion, the die wall and punch#1 were assumed to be stationary. Punch#2 was assumed to move and extrude the upsetted work piece. Once the work piece was extruded, punch#2 was retracted back to its original position. The above procedure was repeated four times to simulate 4 RUE cycles.

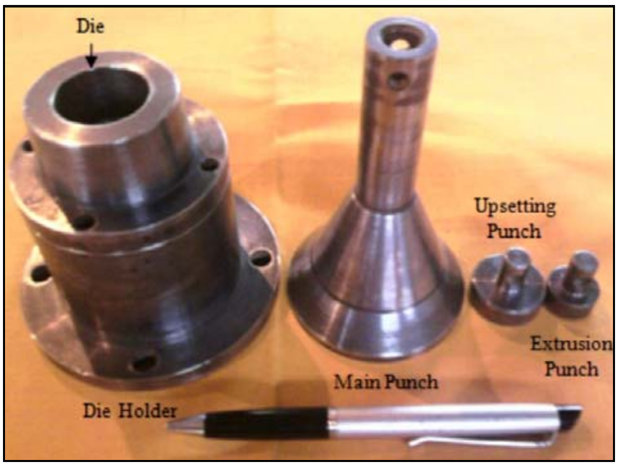

Fig. 5. RUE experimental setup – a two part die and a three part punch.

5.2. RUE experiments

To evaluate the deformation behaviour of bulk materials in the modified die and to validate the results of numerical analysis experimentally, bulk CP Cu was subjected up to 4 RUE cycles at room temperature. The die cavity and the copper samples were coated with Molykote® D-321R spray to reduce friction. The die and punch assembly used to carry out RUE experiments are shown in Fig. 5. Details on the die-punch assembly and procedure followed are discussed else-

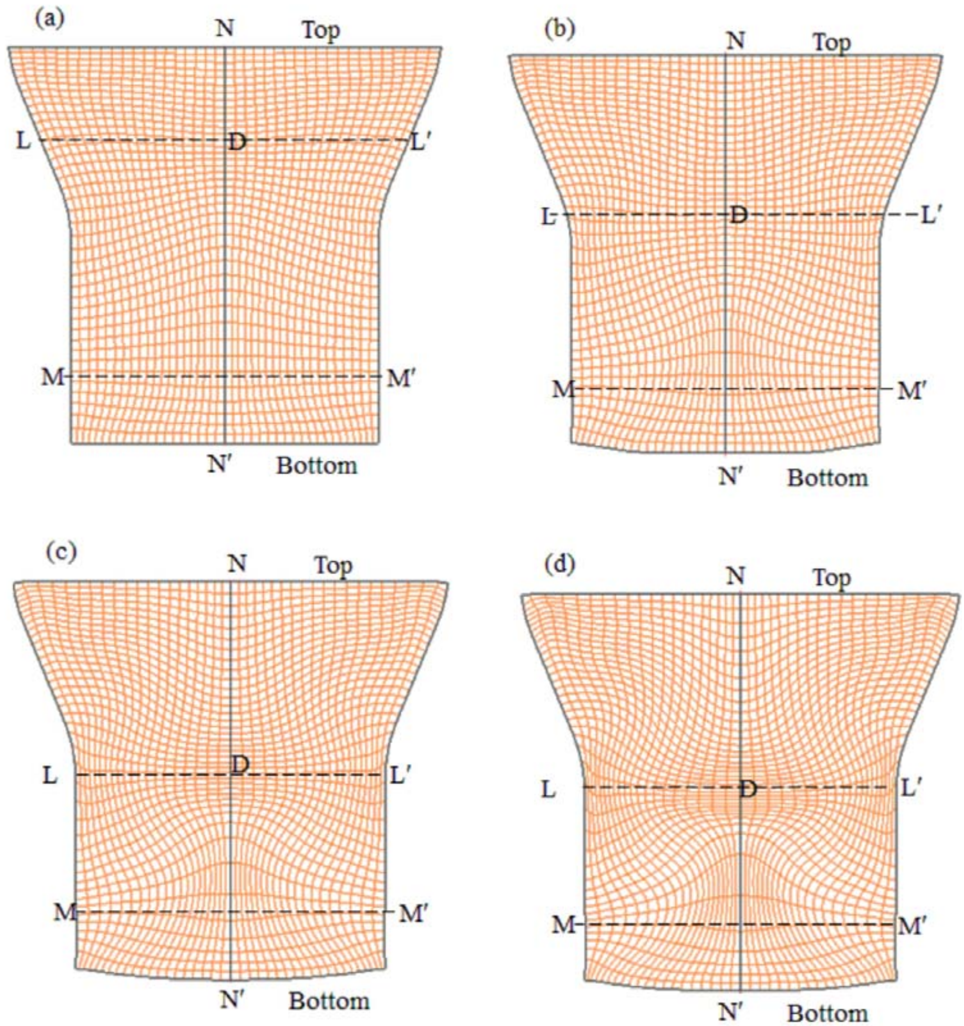

Fig. 6. Deformation pattern of CP Cu obtained at the end of RUE after (a) cycle # 1, (b) cycle # 2, (c) cycle # 3, and (d) cycle # 4.

where [8]. A CP Cu sample after each RUE cycle was preserved. The preserved samples were then vertically cut into two halves. One half of the cut sample was hot mounted, polished and subjected to metallographic investigation. To evaluate the deformation or grain flow pattern, the polished samples were macroetched using a mixture of 80 ml water, 10 grams of potassium dichromate and 5 ml of hydrochloric acid and the resulting material flow pattern was recorded.

6. Results and discussion

6.1. Deformation pattern

The deformation pattern obtained from the finite element analysis at the end of each RUE cycle is shown in Fig. 6a–d. Though a cylindrical work piece was used for the study, the work piece takes the shape of a truncated wedge at the end of RUE cycle. The flow lines (both in horizontal and vertical direction), which were originally evenly spaced and straight in the undeformed sample, attain a wave pattern during deformation. The waviness of the flow line was found to increase with increasing RUE cycles. Based on the shape and direction of the horizontal flow lines, the entire work piece can be divided into three regions using lines LL′ and MM′ as shown in Fig. 6a–d. Further, the flow lines were found to be compressed together at region D (Fig. 6a) along the axis of symmetry NN′. With increasing number of RUE cycles, region D increases in size and moves towards the bottom of the sample.

The deformation behaviour of the work piece during the upsetting stage of first RUE cycle is shown in Fig. 7a–d. As the work piece is pushed in to upsetting volume V_u, where V_u = vol#2 + vol#1 is shown in Fig. 7a, punch#2 acts an upsetting die and restricts the movement of work piece along the vertical direction, this causes the compression of flow lines along

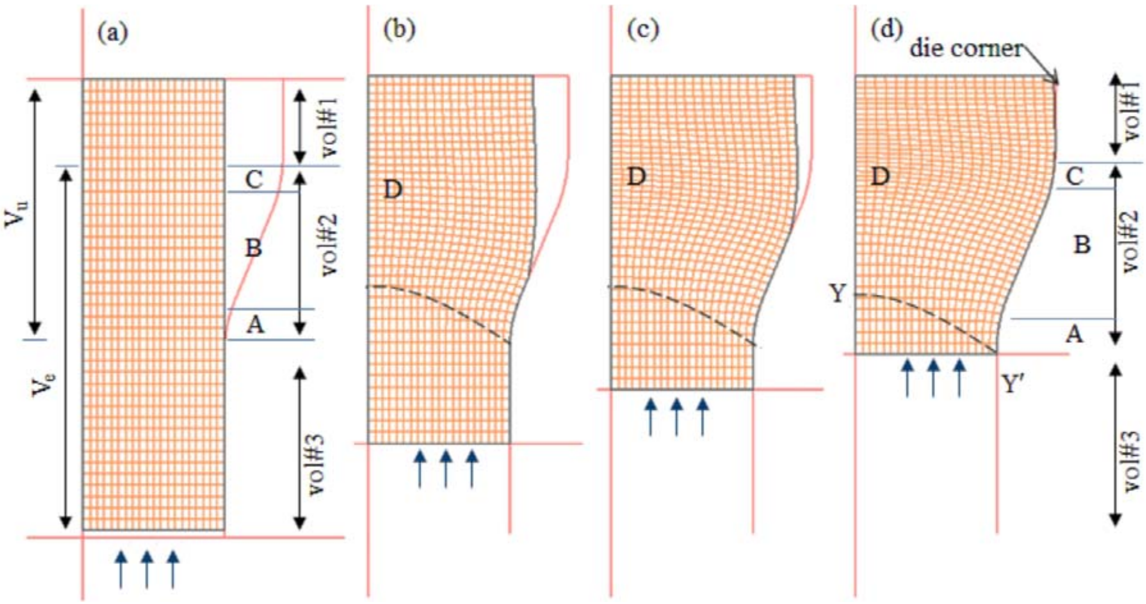

Fig. 7a–d. Deformation behaviour of CP Cu during the upsetting stage of first RUE cycle.

the axis of symmetry (region A). As the vertical movement is restricted and punch#1 is still pushing the work piece into V_u, the work piece starts to flow along the horizontal direction to fill the die cavity. This horizontal flow of work piece to fill V_u causes the horizontal and vertical flow lines to curve. Further, the horizontal flow lines were found to be in convex shape below region D. As a plane of work piece is pushed into the upsetting volume, the work piece material adjacent to the die wall starts to flow in horizontal direction whereas the work piece material at the centre or at the axis of symmetry first moves along the vertical direction and then starts to flow along the horizontal direction. This variation in deformation behaviour can be attributed to the shape of vol#2 which causes the horizontal flow lines to assume a convex shape. It can also be seen from Fig. 7a–c that during upsetting, a part of the work piece still remains in vol#3. Due to the constraint imposed by the die wall, this portion of work piece in vol#3 does not experience any deformation till it enters vol#2. As the last part of the work piece is pushed in to the upsetting volume V_u by punch#1 (along the vertical direction), it displaces the adjacent material to flow in horizontal direction to fill the die cavity. This inverted U-shaped region of the work piece which enters V_u during the final stage of upsetting does not experience any deformation. The undeformed mesh or flow lines in this inverted U-shaped region (delineated by YY′ in Fig. 7b–d) substantiates the fact that this region of work piece does not experience any deformation.

The deformation behaviour of the upsetted sample during the extrusion stage of first RUE cycle is shown in Fig. 8a–d. As the upset material is extruded by punch#2, the work piece exits vol#2 and enters vol#3. Due to the presence of friction between the work piece and the die wall, the work piece has least resistance to deformation along the axis of symmetry and hence the leading end of the work piece extrudes with a concave shape as shown in Fig. 8a–c. Punch#1 restricts the vertical movement of the leading end and assists in filling up the die completely. It can be noted that the die corners are filled only at the final stages of extrusion. Based on the orientation of horizontal flow lines, the extruded sample can be divided into three regions – P, D and Q as shown in Fig. 8b–d. It can also be seen that this difference in the orientation of horizontal flow lines becomes more prominent with increasing RUE cycles (Fig. 6b–d). The vol#2 region which acts as deformation zone during extrusion can be divided into three regions – A, B and C as shown in Fig. 7d. In region B, the diameter varies linearly. The nonlinear variation of work piece (or the die) diameter in regions A and C is marginal as a fillet radius of only 10 mm was provided. During extrusion, till portion of work piece which filled the region A of vol#2 is extruded, the horizontal flow lines are oriented towards along the extrusion direction (Fig. 8b–d). When the work piece that filled region B of vol#2 during upsetting is extruded, the horizontal flow lines are oriented opposite to the extrusion direction. As the diameter of the work piece is reduced during extrusion, there is a flow of material from rim to the centre or axis of symmetry to maintain a constant volume. This inward movement of material causes a gradual increase in height of mesh and hence increases the convexity of the horizontal flow line. The elements with reduced height and increased width at the rim and vice versa at the centre concur well with the above statement (region P in Fig. 8b–d). Further, as the diameter of the

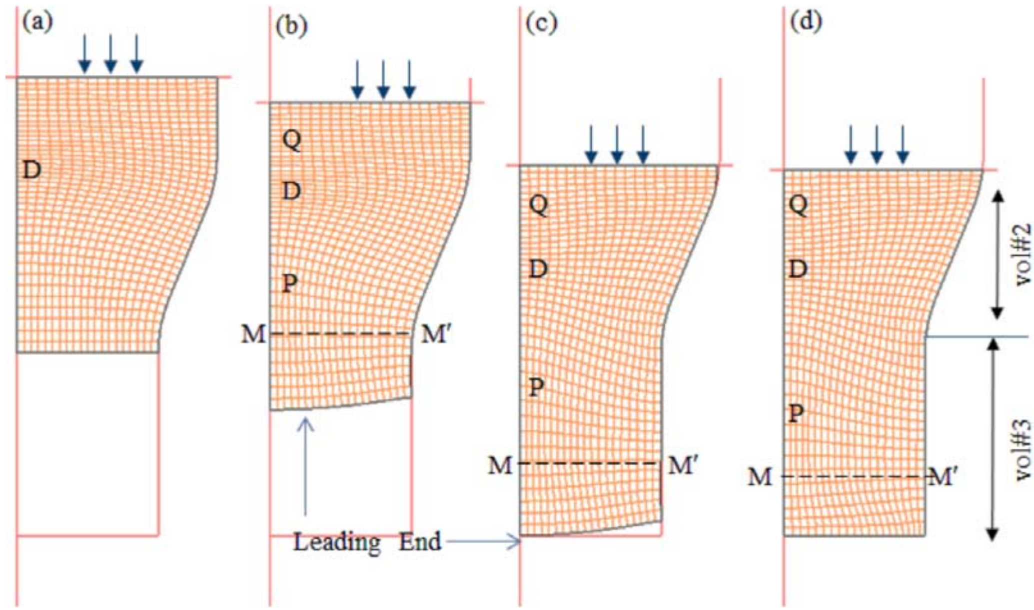

Fig. 8a–d. Deformation behaviour of CP Cu during the extrusion stage of first RUE cycle.

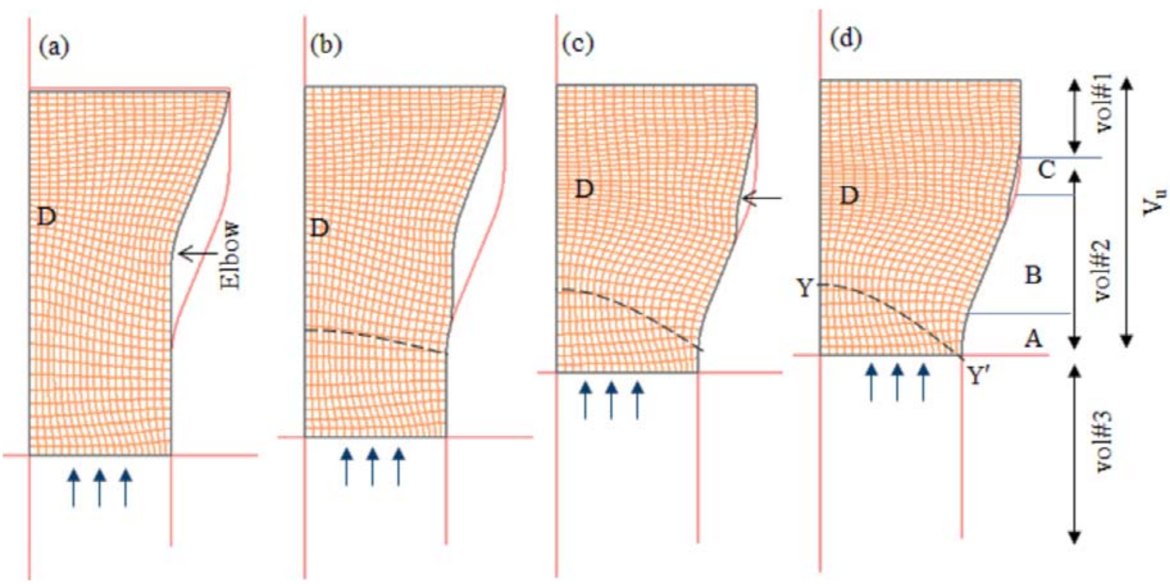

Fig. 9a–d. Deformation behaviour of CP Cu during upsetting stage of second RUE cycle.

work piece material that filled region B of vol#2 varies linearly, the diameter and hence the volume of work piece that tries to exit the deformation zone during extrusion also increases. This increase in volume manifests in further increasing the convexity or orientation of the horizontal flow. When the work piece material that filled vol#1 during upsetting enters and fills the deformation zone (vol#2) during extrusion, the horizontal flow lines are oriented again towards the extrusion direction (region Q). This is because only the rim portion of the material experiences deformation. It can also be seen that, in the extruded work piece (Fig. 8b–d), region D where the mesh was compressed together during upsetting is still present with a marginal increase in the mesh height due to extrusion. This implies that this region experiences deformation during the extrusion process in the modified die which was not the case in the original die design [11].

During the upsetting stage of second RUE cycle, the truncated wedge shaped work piece geometry obtained at the end of first RUE cycle becomes the starting work piece. Due to the shape of the work piece, it can be seen that the top region of vol#1 (i.e., region adjacent to punch#1) is filled even before the beginning of upsetting process as shown in Fig. 9a. The deformation behaviour of the work piece during the up-

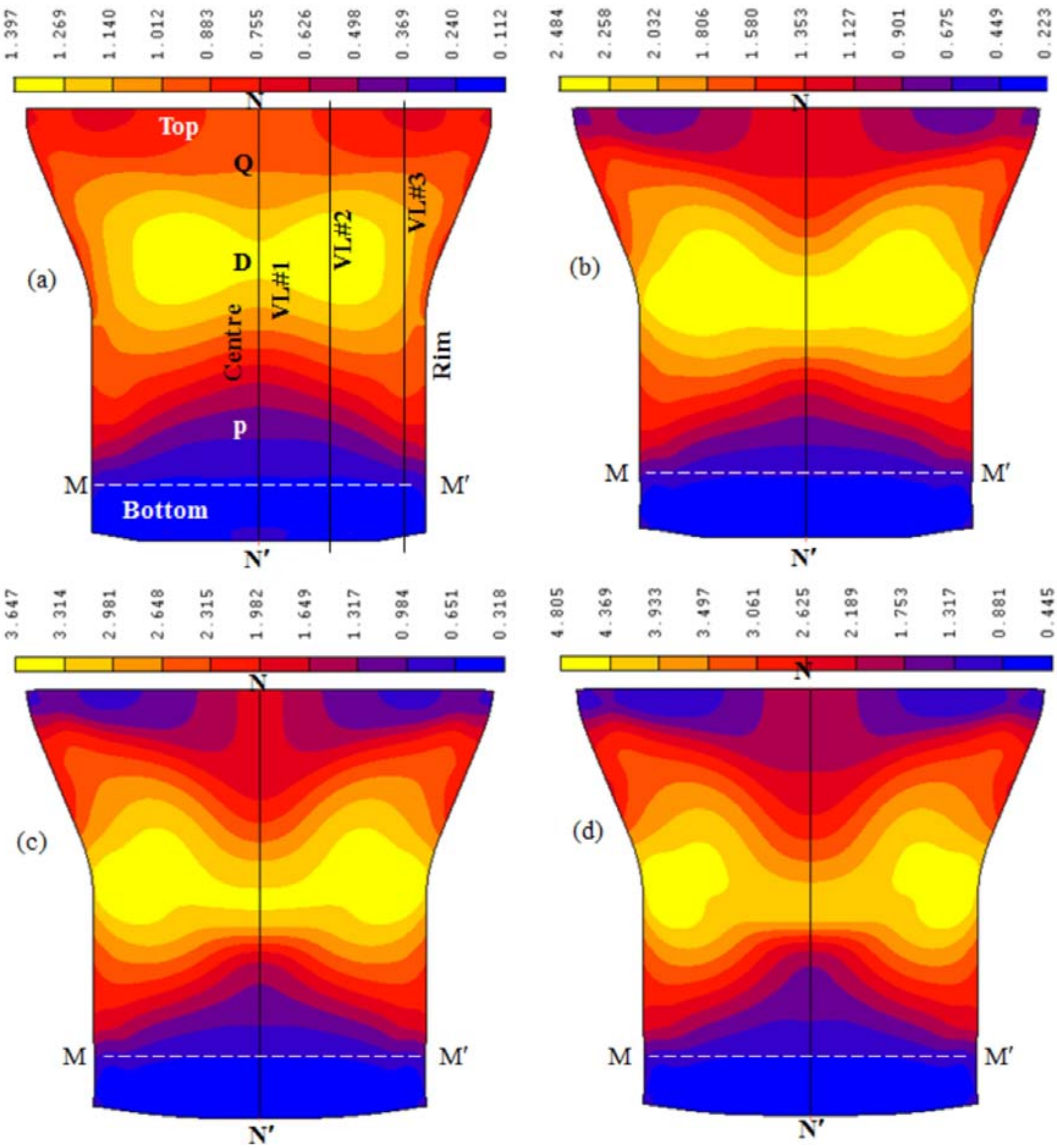

Fig. 10a–d. Total equivalent plastic strain distribution at the end of RUE after (a) cycle # 1, (b) cycle # 2, (c) cycle # 3, and (d) cycle # 4.

setting stage of second RUE cycle (Fig. 9a–d) is quite different to that observed during the upsetting stage of first upsetting cycle (Fig. 7a–d). This difference in the deformation pattern can be attributed to the difference in the work piece geometry. During upsetting, the elbow region present in the work piece hinders the smooth deformation of work piece. As the elbow region offers resistance to deformation (i.e., acts as a virtual base), the work piece below this region starts to fill the die cavity by flowing along the horizontal or lateral direction. This causes further waviness in the vertical flow lines and compression in the mesh height at region D. As deformation progresses, the material at the elbow region also deforms and flows along the horizontal direction to fill the die cavity (V_u). It can be noted that unlike the upsetting stage of first RUE cycle where the die corner gets filled during the final stage of upsetting, the filleted region C is filled last during the upsetting stage of second RUE cycle.

The deformation behaviour of the work piece during the extrusion stage of second RUE cycle and subsequent RUE cycles are similar to that as explained above except for the increases in the intensity of deformation at region D and the waviness of the flowlines caused due to the presence of the elbow region.

6.2. Total equivalent plastic strain distribution

The total equivalent plastic strain (TEPS) contours obtained from the finite element analysis are

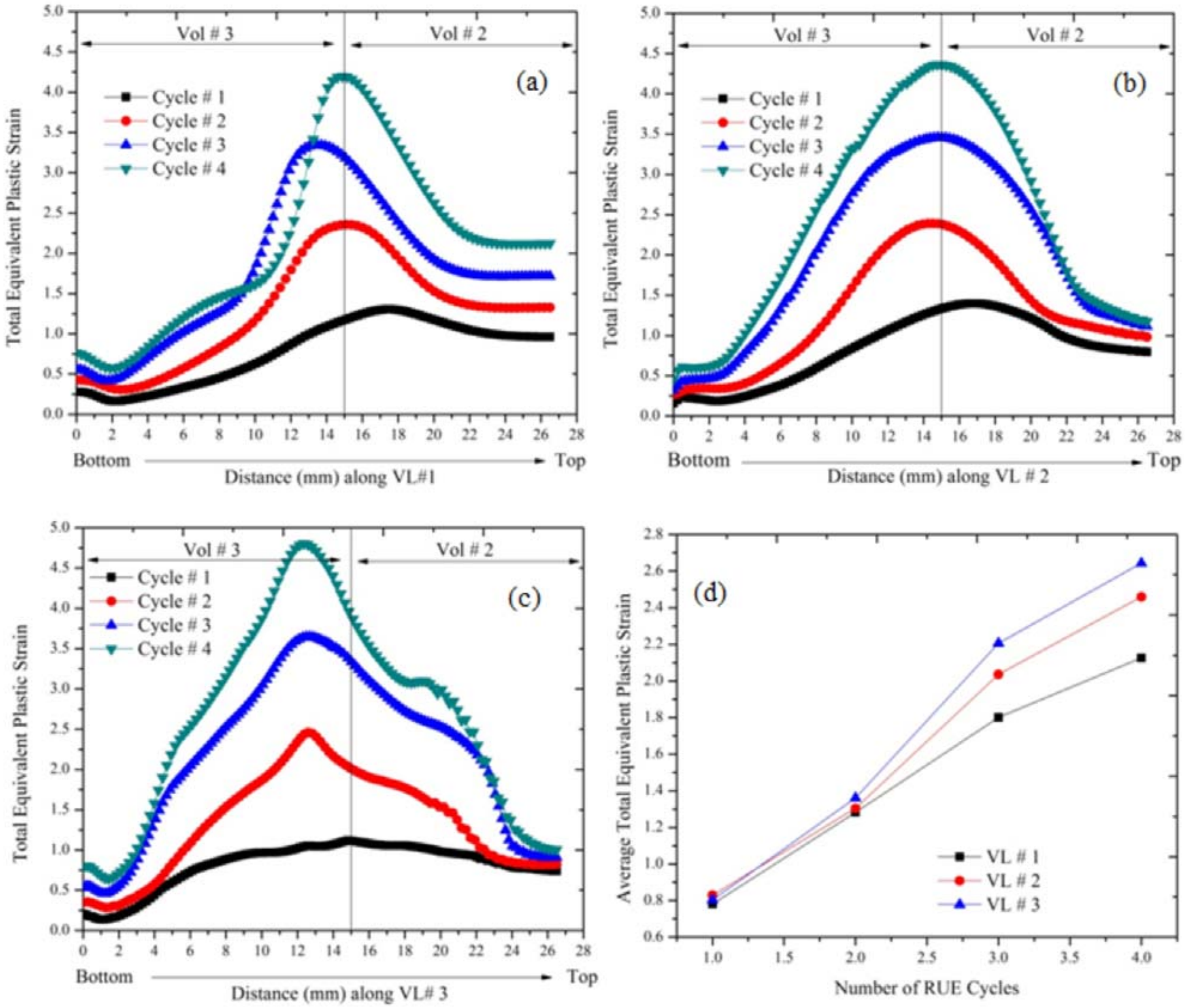

Fig. 11. Variation of total equivalent plastic strain along (a) VL#1, (b) VL#2, (c) VL#3, (d) variation of average total equivalent plastic strain along VL#1, 2 and 3 with respect to the number of RUE cycle.

shown in Fig. 10a–d. It can be noted that, irrespective of the number of RUE cycle, the maximum value of strain is observed at region D which lies at the intersection of vol#2 and vol#3. Further, it can also be noted that the variation of strain along the horizontal direction (centre to rim) is rather marginal. However, there is a large variation in strain along the vertical direction (from bottom to top). In the original RUE die design, it has been reported that there is a large variation in strain along both the horizontal and vertical directions [11]. In order to evaluate the strain variation and homogeneity achieved using the modified die design, the strain values along three vertical lines across the cross-section of the sample as shown in Fig. 10a were estimated. The variation of TEPS from bottom to top along the vertical lines VL#1, 2 and 3 with increasing number of RUE cycles are shown in Fig. 11a–c. It can be seen that irrespective of the number of RUE cycle and the location of the vertical line, the strain increases initially (approximately till the intersection of vol#2 and 3 is reached), reaches a peak, thereafter decreases and attains a steady value. This variation in strain can be attributed to the deformation behaviour during the upsetting and extrusion stages of RUE cycle as explained above. It can also be noted that the variation in strain along the vertical direction increases with increasing RUE cycles as shown in Fig. 11a–c. It is also noticeable that up to a distance of nearly 2 mm from the bottom of the sample (region below line MM′ in Fig. 11 a–c), the increase in strain is very marginal with increasing number of RUE cycle when compared to other regions. Further, the magnitude of strain in this region is very small compared to the peak strain in any particular cycle. This implies that this region of the material has experienced very little deformation. This observation concurs well with the observations based on the flow lines.

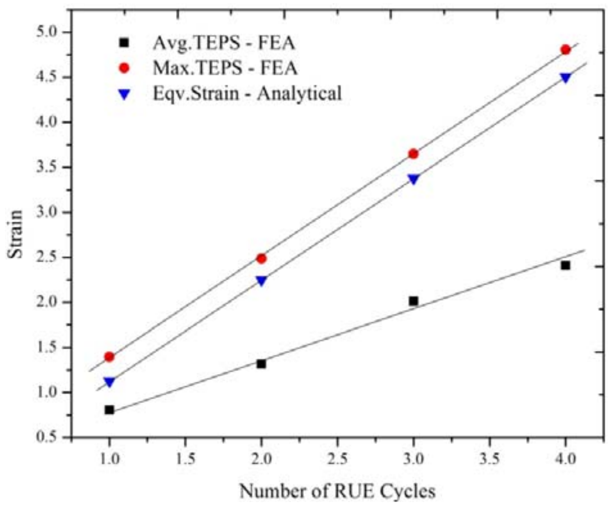

Fig. 12. Variation of average strain with respect to number of RUE cycle.

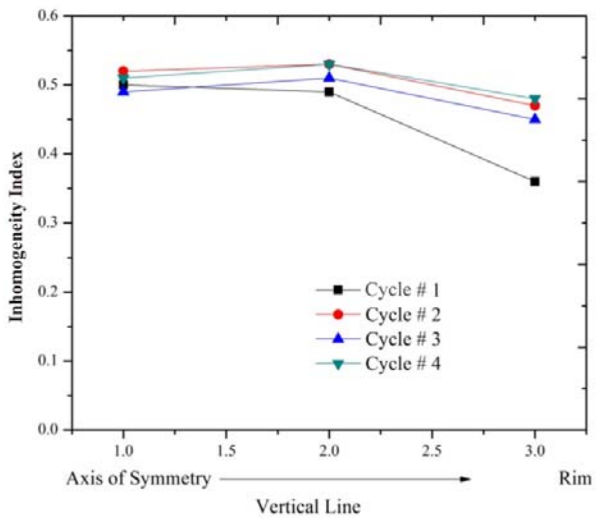

Fig. 13. Variation of inhomogeneity index across the cross-section of the sample.

The average total equivalent plastic strain (Avg. TEPS) along the vertical lines (VL#1, 2 and 3) was evaluated and plotted as a function of increasing RUE cycles (Fig. 11d). The results obtained indicate that the average TEPS along any particular vertical line increases with increasing number of RUE cycle. Further, it may also be inferred that the variation of average strain between the vertical lines (VL#1, 2 and 3) increases with increasing number of RUE cycle. This can be attributed to the difference in the gradient of strain present along the vertical lines with increasing RUE as shown in Fig. 11a–c.

The average strain across the cross-section of the sample was estimated from FEA and compared with the analytical equivalent strain. It can be seen from Fig. 12 that the average strain estimated from FEA is lower than that estimated by the analytical equation. Further, it can also be noted that the difference between the FEA estimated average strain and the analytical strain increases with increasing number of RUE cycle. This can be attributed to the presence of strain gradient within the sample which increases with increasing number of RUE cycles. To substantiate the statement, the peak or maximum strain observed in the RUE processed sample was compared with the analytical strain as shown in Fig. 12. As the variation of maximum or peak strain concurs well with the variation of analytical strain, it can be said that by increasing the homogeneity of deformation or reducing the strain gradient in the processed sample, the average strain can be made to match the analytical strain.

6.3. Strain inhomogeneity

The degree of strain inhomogeneity [11] can be estimated using the following equation:

$$\mathrm{CV}\varepsilon_{\mathrm{p}} = \frac{\mathrm{Stdev}\,\varepsilon_{\mathrm{p}}}{\mathrm{Avg}\,\varepsilon_{\mathrm{p}}}. \tag{3}$$

In the expression, $\mathrm{CV}\varepsilon_{\mathrm{p}}$ represents the coefficient of variance of TEPS, Stdev ε_{p} is standard deviation of total equivalent plastic strain and Avg ε_{p} is the average total equivalent plastic strain along a cross-section. The strain inhomogeneity index estimated using Eq. (3) along the three vertical lines after each RUE cycle is shown in Fig. 13. A lower value of coefficient of variance indicates better homogeneity. It can be seen that the inhomogeneity in strain decreases from centre to the rim irrespective of the number of RUE cycle. However, there is an increase in inhomogeneity with increasing number of RUE cycle along all the vertical lines. This can be attributed to the strain gradient present in the material.

6.4. Macro- and microstructure of RUE processed copper

Commercial pure copper samples processed using the original and modified die design are shown in Fig. 14a and 14b, respectively. The absence of extrusion defect in the samples processed using the modified die can be readily seen. The cross-sections of the samples processed up to 3 RUE cycles using the original and modified die are also shown in Fig. 14c,d. It can be seen that the extrusion defect formed in the original die design has almost penetrated into vol#3. This portion of material has to be discarded for obvious reasons. The absence of axial hole or folds up to 4 RUE cycles indicates that the current modified die

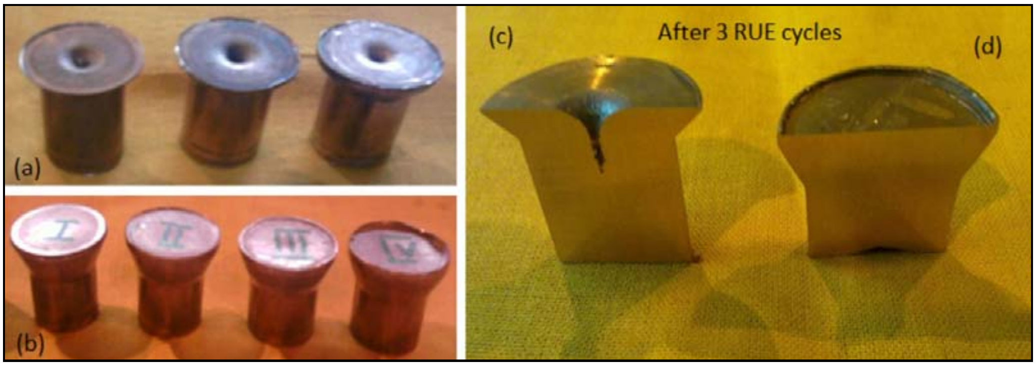

Fig. 14. Copper samples processed using (a) original die design showing axial hole at top, (b) modified die shown no defect. (c) and (d) cross-section of sample processed up to 3 RUE cycles using the original and modified die design respectively.

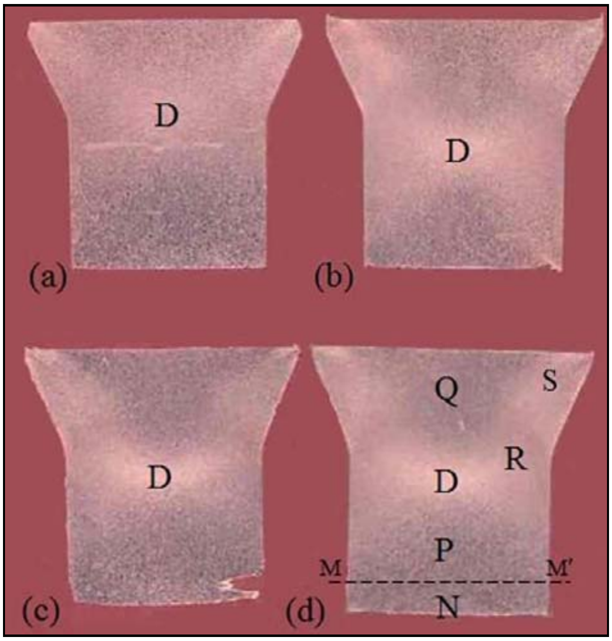

Fig. 15. Macrostructure of RUE processed CP Cu after (a) cycle # 1, (b) cycle # 2, (c) cycle # 3, and (d) cycle # 4.

design can be successfully used to impart severe plastic deformation in bulk materials using the repetitive upsetting-extrusion process. The deformation or grain flow pattern obtained after macroetching the RUE processed copper samples are shown in Fig. 15a–d. A clear matching in terms of deformation pattern and strain concentrations can be observed between finite element analysis (Fig. 6) and the actual experiments (Fig. 15a–d) carried out on commercial pure copper. The microstructure observed at various locations in the work piece subjected to 4 RUE cycles (Fig. 16) not only concurs well with the deformation pattern (Fig. 6d) and the strain distribution (Fig. 10d), but also represents the mechanism of grain refinement that is typical of severe plastic deformation as reported by various researchers [1, 4, 5, 17]. Though a significant amount of grain refinement has been achieved within 4 RUE cycles as shown in Fig. 15e (at regions D and R), there is a large variation in the degree of deformation imparted which manifests in the large variation in the grain size. If the strain gradient or deformation heterogeneity can be reduced by further optimizing the design or processing sequence, the homogeneity of the process can be improved and hence uniformity in grain refinement can be achieved.

7. Summary

From the numerical analysis and the actual experiments carried out on commercial pure copper it can be concluded that the modified die design can be successfully used to process bulk materials without imparting defects such as an axial hole or fold. Though the modified die design has improved the deformation behaviour in terms of strain distribution and homogeneity along the horizontal direction and across the work piece, the process design has to be improved to reduce the large strain gradients that are observed along the vertical direction. This large variation of strain manifests in reducing the homogeneity and hence the higher uniformity of grain refinement that can be achieved. The bottom region of the RUE processed work piece experiences very low strain. The process may be initiated with extrusion instead of upsetting; this should help in imparting strain to the bottom of the sample as well as in reducing the strain gradient. However, extensive studies need to be carried out before arriving at an optimum processing scheme.

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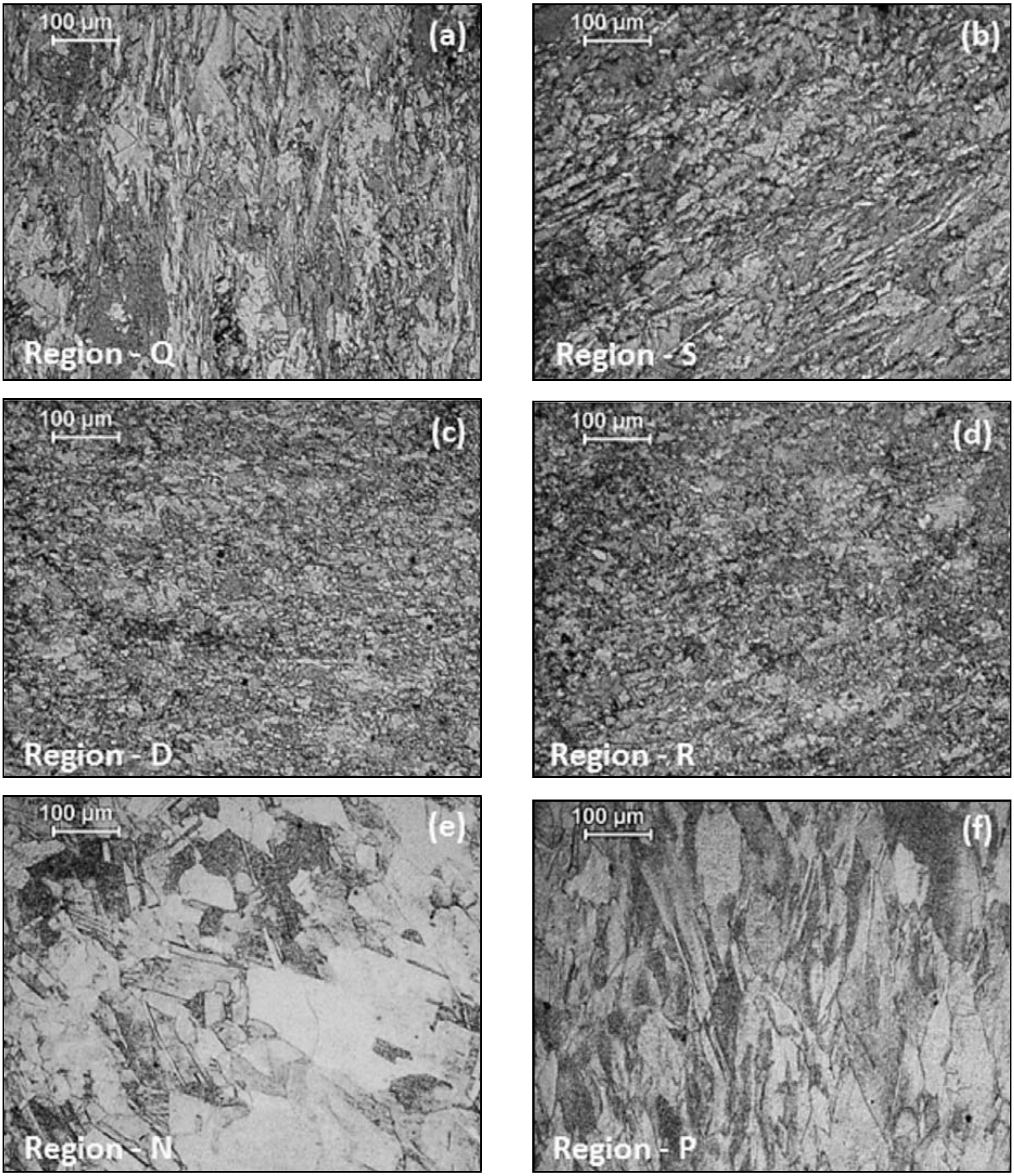

Fig. 16a–f. Microstructure obtained at various locations (shown in Fig. 15d) in the work piece subjected to 4 RUE cycles.

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