

# On the die design for Repetitive Upsetting – Extrusion (RUE) process

I. Balasundar · T. Raghu

Received: 18 September 2010 / Accepted: 11 November 2011 / Published online: 10 December 2011  
© Springer-Verlag France 2011

**Abstract** Though the capability of Repetitive Upsetting-Extrusion (RUE) process to produce ultrafine grains in a bulk aluminium alloy has been established, a detailed description on the material flow, deformation homogeneity and the die design requirements to process bulk materials has never been addressed. To address these issues commercial pure copper (CP Cu) was subjected up to four cycles of RUE using the die design that has been used by various researchers. The RUE processed CP Cu samples when subjected to macrostructure and microstructure evaluation revealed that apart from inhomogeneous deformation, defects such as axial hole/funnel and folds/laps were induced in the processed samples. The formation of these defects during RUE is attributed to the current die design. Based on a recent study carried out on the extrusion defect – axial hole/funnel, a modified RUE die design has been proposed. CP Cu subjected to RUE using the modified die design revealed that the modified die design not only helps in avoiding the defects but also improves the homogeneity.

**Keywords** Upsetting · Extrusion · SPD · RUE · Copper

## Introduction

Driven by the need to produce nano or ultrafine grains in bulk materials, a variety of severe plastic deformation (SPD) processes have come in vogue [1–4]. These ultrafine (100 nm < grain size <1 µm) or nano grained

(grain size <100 nm) materials produced by these processes exhibit superior strength and ductility, super-plasticity at low temperatures and high strain rates, high wear resistance, high corrosion resistance and enhanced fatigue life [1–4]. These SPD processes can be broadly classified into two categories (i) bulk materials processing and (ii) sheet materials processing. In bulk SPD processes, the work piece has a high volume to surface ratio whereas sheet SPD processes use materials with low volume to surface ratio [2, 3]. Processes such as Equal Channel Angular Pressing [5–7], Cyclic Extrusion and Compression [8], High Pressure Torsion [9], etc. fall under bulk SPD processes, Accumulative Roll Bonding [10], Asymmetric Rolling [11], Repetitive Corrugation and Straightening [12], Constrained Groove Pressing [13] fall under sheet SPD processes. All these processes have been designed for a particular application and have different technical characteristics.

Among the above mentioned processes, Repetitive Upsetting-Extrusion (RUE) is a new severe plastic deformation process that is being employed to process bulk materials. In this process, the work piece or material is subjected to repeated upsetting and extrusion. As both the upsetting and extrusion processes are currently used in industrial scale, scaling up of RUE process is more readily viable than any other severe plastic deformation process. Though Aizawa and Tokimutu [14] originally invented the process to deform powder materials for bulk mechanical alloying, Hu Lianxi et al. [15] used the process to deform a bulk aluminium alloy using the same die design that was used by Aizawa and Tokimutu [14]. It is important to know and understand the deformation behaviour of bulk materials during RUE and also to ascertain the deformation homogeneity that can be achieved. This knowledge which is currently not available

I. Balasundar (✉) · T. Raghu  
Near Net Shape Group, Aeronautical Materials Division, Defence Metallurgical Research Laboratory,  
Hyderabad 500 058, India  
e-mail: i\_balasundar@yahoo.com

would help in scaling up the process for commercial applications. Though Hu Lianxi et al. [15] established that the process is capable of producing ultrafine grains in bulk LY12 Al alloy, a detailed description on the material flow/behaviour and deformation homogeneity that can be achieved was not reported. Further, as the deformation behaviour of powder and bulk materials are quite different, it is not clear whether the same die design can be used to process both powder as well as bulk (solid) materials. To address these issues RUE experiments on CP Cu were carried out using a die design similar to that used by various researchers [14, 15]. Macrostructure and microstructure was evaluated across the RUE processed samples to ascertain the deformation behaviour and homogeneity. Based on the experimental observations, a modified die design has been proposed. CP Cu samples were again subjected to RUE using the modified die design. The results obtained from the study are presented and discussed here.

### RUE process

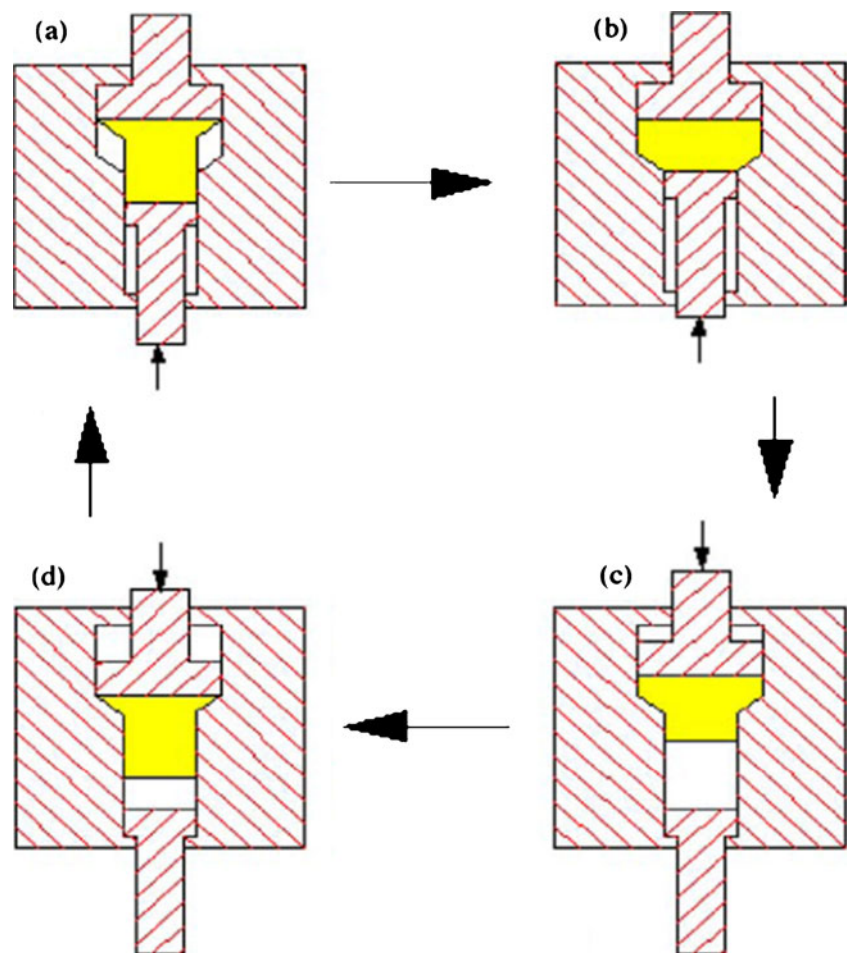
A typical RUE process or cycle consists of two basic stages (i) upsetting and (ii) extrusion as shown in Fig. 1. In RUE

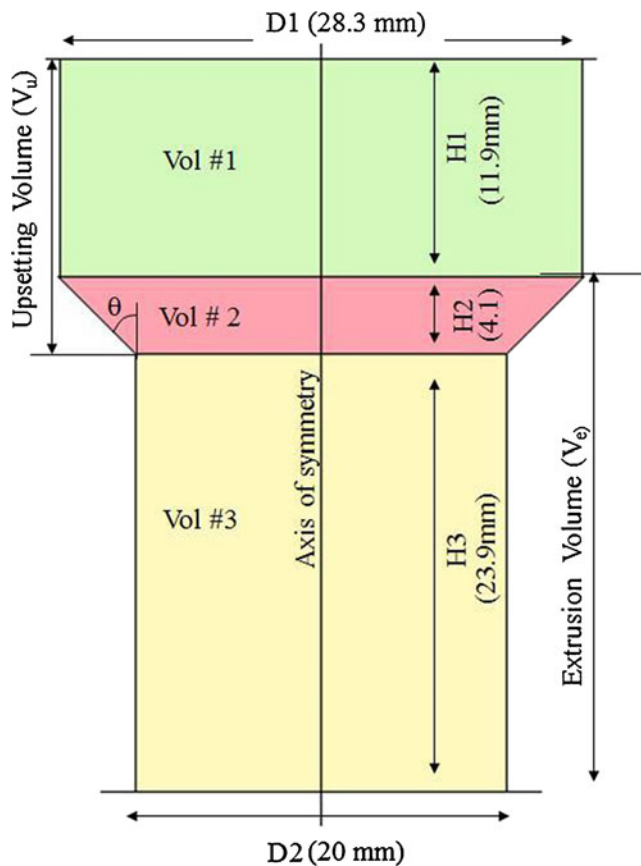
process, a cylindrical work piece of known dimension is first subjected to upsetting, wherein, the height is reduced and the cross-sectional area is increased. The upsetted work piece is subsequently subjected to extrusion, wherein the height is increased and the cross-sectional area is reduced. During upsetting the flow of material is perpendicular to the upsetting direction whereas during extrusion the material flow is parallel to the upsetting or extrusion direction. This reversal of flow is believed to refine the grain size [15].

### Current RUE die design

RUE die design that is being currently used by various researchers to process metal powders [14] and bulk material [15] can be divided into three parts each having a volume  $V_1$ ,  $V_2$ , and  $V_3$  respectively as shown in Fig. 2. These volumes are designed in such a way that  $V_1 + V_2 = V_2 + V_3$ . During upsetting the work piece fills the volume  $V_u = V_1 + V_2$  whereas it fills the volume  $V_e = V_2 + V_3$  during extrusion. Volume of the work piece ( $V_w$ ) is therefore given by  $V_w = (V_1 + V_2) = (V_2 + V_3)$ . In the existing RUE die design that has been used by various researchers [14, 15], the height of

**Fig. 1** Typical RUE cycle [15]





**Fig. 2** Existing RUE die design that is being used by various researchers [14, 15, 19]

volume  $V_2$  is kept at a minimum to ensure that major portion of work piece is subjected to either upsetting or extrusion. In conventional forming, the aspect ratio (height to diameter ratio of the work piece) during upsetting and extrusion ratio (ratio between initial and final cross sectional area) during extrusion are two important parameters that influence the deformation behaviour, strain distribution and load requirement [16, 18]. For the current study, the aspect and extrusion ratio was fixed at 1.5 and 2.0 respectively. The RUE die has been designed to impart an axial true strain of  $\epsilon = 2 \ln(D_1/D_3) = 0.693$  either during an upsetting or extrusion operation. The total strain at the end of an RUE cycle i.e., after an upsetting and extrusion operation would therefore be 1.386. The die design used in the study is similar to that used by Aizawa [14] and Hu Lianxi et al. [15].

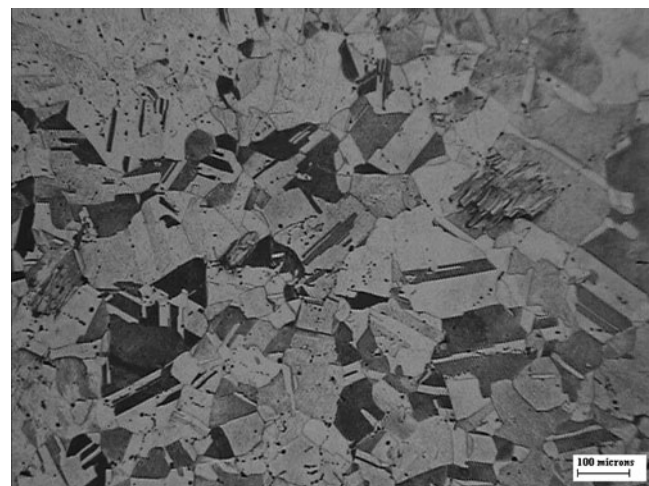
### RUE of CP Cu using the current die design

#### RUE experiments

Commercial pure copper with a nominal composition of 99.9 Cu - 0.04Zn - 0.06O (wt%) was procured in the form

of 50 mm diameter rods. The material was found to have a mixture of coarse and fine grains (Fig. 3). The average grain size of the as-received material was estimated to be  $95 \mu\text{m}$ . The average microhardness of the as-received material measured using a knoop hardness tester with 50 g load was  $107 \pm 3 \text{ mHv}$ . Six cylindrical work pieces ( $\phi 20 \times 30 \text{ mm}$ ) were electrode discharge machined from the as-received bar to carry out RUE experiments at room temperature.

As a bi-directional press facility was not available, a two part die and a three part punch assembly was designed and fabricated out of H-13 tool steel to carry out the RUE experiments on a unidirectional press. The die assembly consists of die and die holder whereas the punch assembly contains a main punch, upsetting punch and extrusion punch. The RUE die containing the cavity i.e., Volumes  $V_1$ ,  $V_2$  and  $V_3$  was fixed to the die holder. After the initial upsetting, the die along with the work piece was inverted to carry out extrusion and vice versa. The main punch was fixed to the press ram. Depending on the forming operation that was being carried out i.e., upsetting or extrusion, appropriate punch was attached to the main punch to carry out the experiment. Prior to deformation, the die and work piece was coated with Molykote® D-321R spray lubricant to reduce friction. Out of the six work pieces, one work piece each was subjected to upsetting and extrusion, the remaining four work pieces were progressively subjected to 4 RUE cycles. A work piece after each RUE cycle was stored in order to evaluate the deformation behaviour. The copper work pieces subjected to RUE cycles were then vertically cut into two halves. One half of each work piece was hot mounted and polished. In order to evaluate the macrostructure, the work pieces were macroetched using a mixture of 80 ml water, 10 g of potassium dichromate and 5 ml of hydrochloric acid. The resulting material or grain flow pattern was recorded. The macroetched work pieces



**Fig. 3** As received microstructure of commercial pure copper

were then repolished and subjected to microstructure evaluation. A mixture of 80 ml water, 10 g of potassium dichromate, 2 ml of sulphuric acid was used to etch the samples. The microstructure at various locations in the work piece was recorded using an optical microscope.

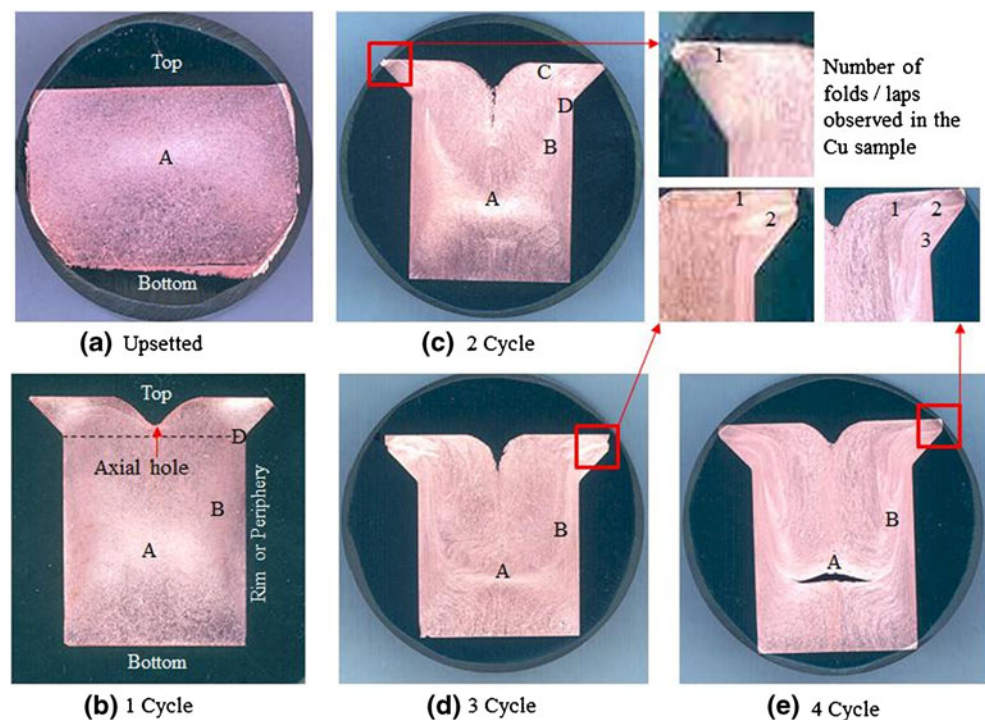
#### Macrostructure of the RUE processed samples

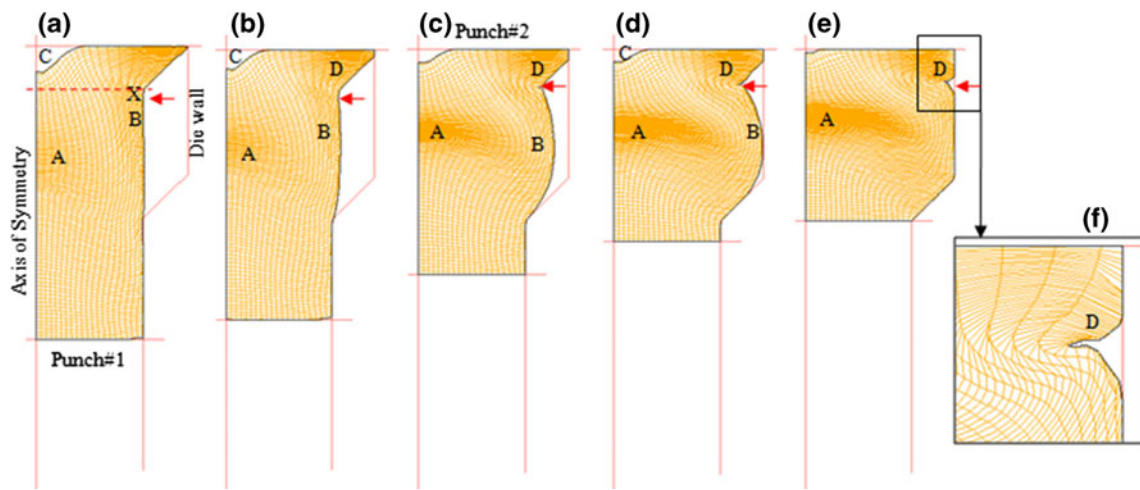
The grain or material flow pattern obtained after macro-etching the RUE processed copper samples are shown in Fig. 4a–e. In the sample subjected to upsetting (Fig. 4a), there is a severely deformed region (region-A) located at the middle of volume  $V_1$ . This severely deformed region-A is oriented perpendicular to the upsetting direction which indicates the direction of material flow during upsetting. Above and below region-A, there is a U-shaped region which has experienced very little or no deformation. This U-shaped region can be attributed to friction hill which is typical of any upsetting process [17]. The presence of vertical flow pattern (region-B) near the rim portion of the work piece in Fig. 4b confirms that when the upsetted work piece is extruded, the rim or periphery of the work piece is subjected to severe deformation. Apart from region-B where the flow pattern is parallel to the extrusion direction, region-A where the flow is perpendicular to the upsetting or extrusion direction is still present in the extruded work piece. This implies that the inhomogeneous deformation experienced by the work piece during upsetting is not rectified by the extrusion process. A U-shaped groove is observed at the mid region on the top surface of the

extruded work piece. This U-shaped groove is known as axial hole or funnel [16–18]. It has been reported that, when extrusion is carried out to a point at which the length of the work piece remaining in the container is nearly equal to one-quarter of its diameter, rapid radial flow of material into the die results in the creation of an axial hole or funnel [16–18]. This axial hole extends for some distance into the extruded work piece as shown in Fig. 4b. This axial hole is a defect and the portion of the material till the depth of the hole or funnel would be discarded in a conventional extrusion process [16, 17]. It has also been reported that the formation of axial hole or funnel defect can be avoided by inclining the face of the ram to the ram axis [17]. Discarding a portion of the work piece or inclining the face of extrusion ram or punch are not viable solutions to avoid the defect formation during RUE. Though RUE experiment was initiated with a cylindrical work piece, it can be seen that at the end of first RUE cycle the work piece attains a T-shaped geometry shown in Fig. 4b.

The grain flow pattern obtained after the second RUE cycle is shown in Fig. 4c. A distorted H-shaped material flow pattern can clearly be seen in the work piece. The axial hole has extended further deep in to the material, cracks or voids are present just below the U-shaped groove or axial hole. At the top corner of the work piece (marked by a square grid), a fold is observed in the wedge shaped region. Fold or lap or cold shut is a defect or discontinuity produced when two surfaces of metal fold against each other without welding properly [16, 17]. Based on the results obtained from the finite element analysis of RUE

**Fig. 4** a–e Macrostructure of the RUE processed CP Cu samples

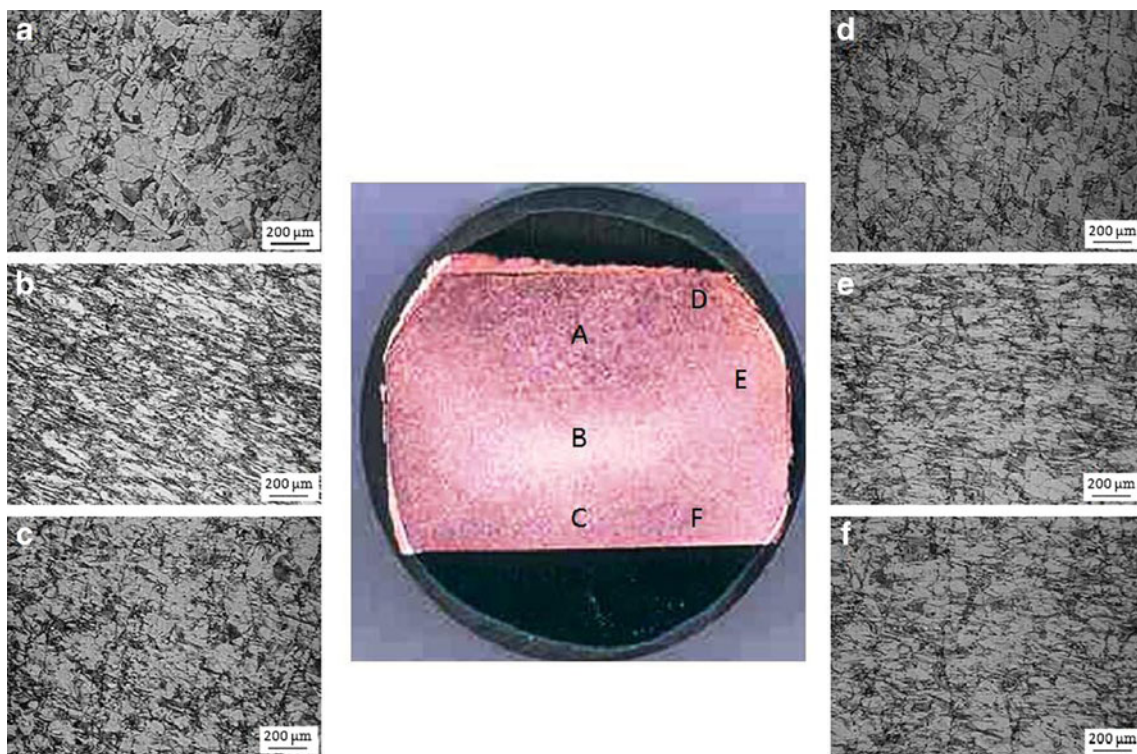




**Fig. 5** a–e Formation of fold during upsetting stage of second RUE cycle

process [19], the formation of fold during an RUE process can be explained as shown in Fig. 5a–e. The T-shaped work piece obtained at the end of first RUE cycle becomes the starting material for upsetting during the second RUE cycle. During the upsetting stage of second RUE cycle, the region above the elbow (i.e., region above the dotted line in Figs. 4b and 5a) is not allowed to expand or deform due to the constraints imposed by the die wall and friction. The material below region-D (Figs. 4b and 5b) starts to deform during upsetting i.e., the material above the dotted line shown in Figs. 4b and 5b acts as a virtual base during the

upsetting process. As deformation progresses, the material flows over this region-D and fills the die cavity (Fig. 5c–e). This causes the fold formation during the upsetting stage of second RUE cycle. The number of folds observed can be seen to be increasing with increasing RUE cycles i.e., in the work piece subjected to 4 RUE cycles, 3 folds can be observed in the wedge shaped region (Fig. 4e). It should be noted that the fold or lap is not observed in the work piece at the end of first RUE cycle (Fig. 4b). This is because; the RUE experiment was initiated with a cylindrical work piece. If the RUE experiment had been initiated with a T-shaped



**Fig. 6** Microstructures at various locations in the work piece subjected to upsetting

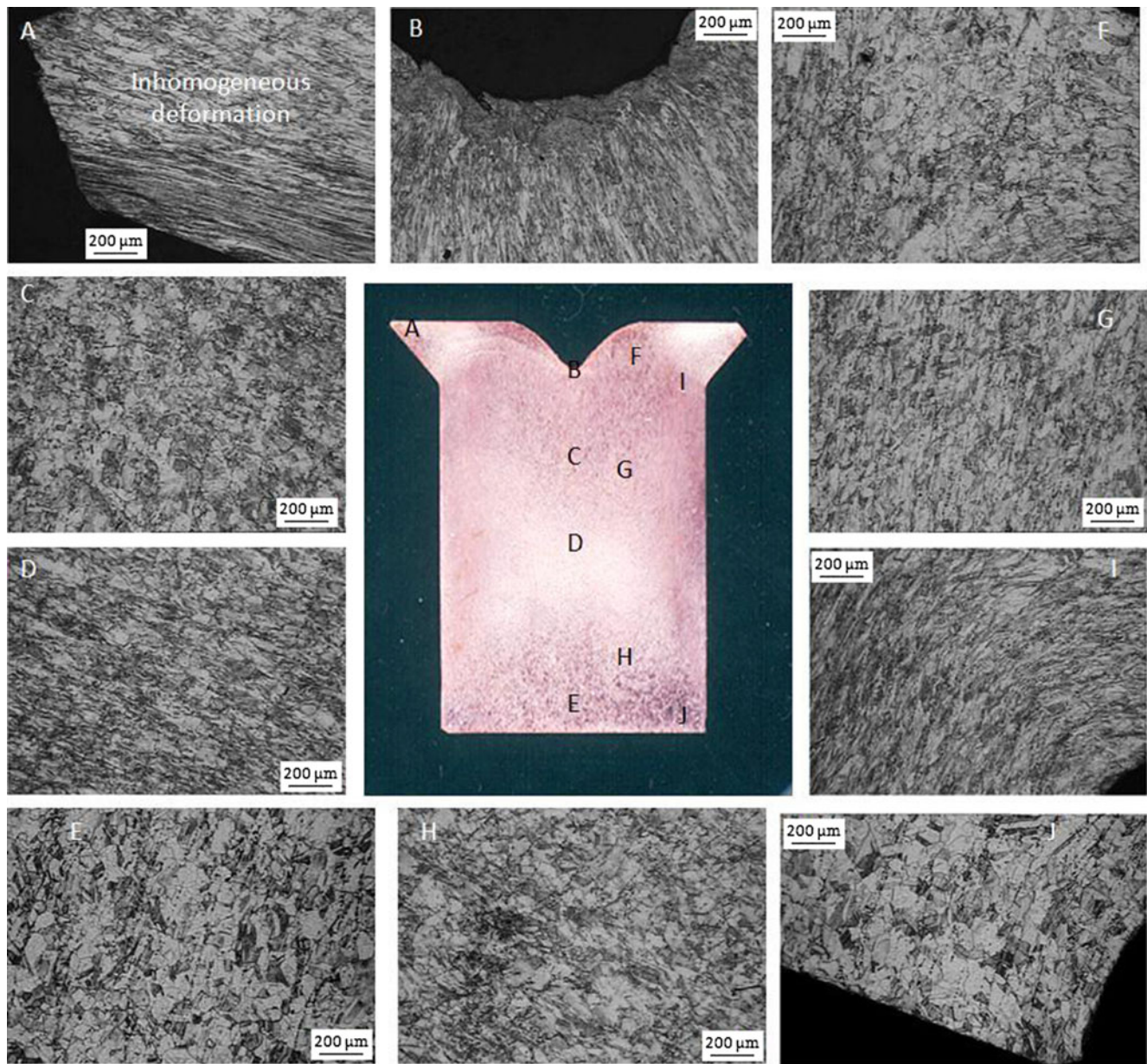
work piece or if the RUE experiment had been initiated with extrusion instead of upsetting, fold formation would have been observed after upsetting at the first cycle itself. From these observations, the formation of fold or lap can be attributed to the T-shaped sample geometry obtained at the end of first RUE cycle.

The H-Shaped metal flow pattern becomes prominent in the work piece subjected to 3 and 4 RUE cycles (Fig. 4d and e). The axial hole or funnel can be seen almost to  $2/3^{\text{rd}}$  of the work piece height. A crack can also be observed at the severely deformed region along the horizontal direction in the work piece subjected to 4 RUE cycles (Fig. 4e). The shape and orientation of the crack observed here is quite

different from the chevron cracks [16, 17, 20, 21] observed during conventional extrusion and the reason for the formation of same is discussed in the succeeding section.

#### Microstructural observations on the RUE processed samples

The microstructure obtained at various locations in the work piece subjected to upsetting (first RUE cycle) is shown in Fig. 6. A severely deformed microstructure can be seen in region-B which indicates that the material has experienced intense deformation as indicated in the macrostructure (Fig. 4a). It can also be noticed that the elongated



**Fig. 7** Microstructure at various locations in the work piece after 1 RUE cycle

grains are perpendicular to the upsetting direction. In region-A, B, D and F, the material exhibits a microstructure similar to the as-received microstructure which indicates that these regions did not experience much deformation. This can be attributed to the friction existing between the work piece, die and punch. In region-D, a moderately deformed microstructure can be seen.

The microstructure obtained at various locations in the work piece at the end of 1 RUE cycle i.e., after upsetting and extrusion is shown in Fig. 7. It can be seen that, near the wedge shaped region-A, the material has experienced inhomogeneous deformation. From the shape of the grains it can be observed the bottom surface is severely deformed

whereas the top surface is only moderately deformed. In region-B and I the material exhibits elongated grains which are oriented along the extrusion direction. From the orientation of grains, it can be concluded that this deformation is imparted during the extrusion stage of RUE cycle. Between region-B and I i.e., in region-F, the material has received very less deformation and a microstructure similar to the starting or initial microstructure (Fig. 3) of the material can be clearly seen. In region-D the deformed grains are oriented perpendicular to the extrusion direction which indicates that this deformation was caused during the upsetting process and extrusion did not alter its orientation. In other words, the effect of extrusion did not

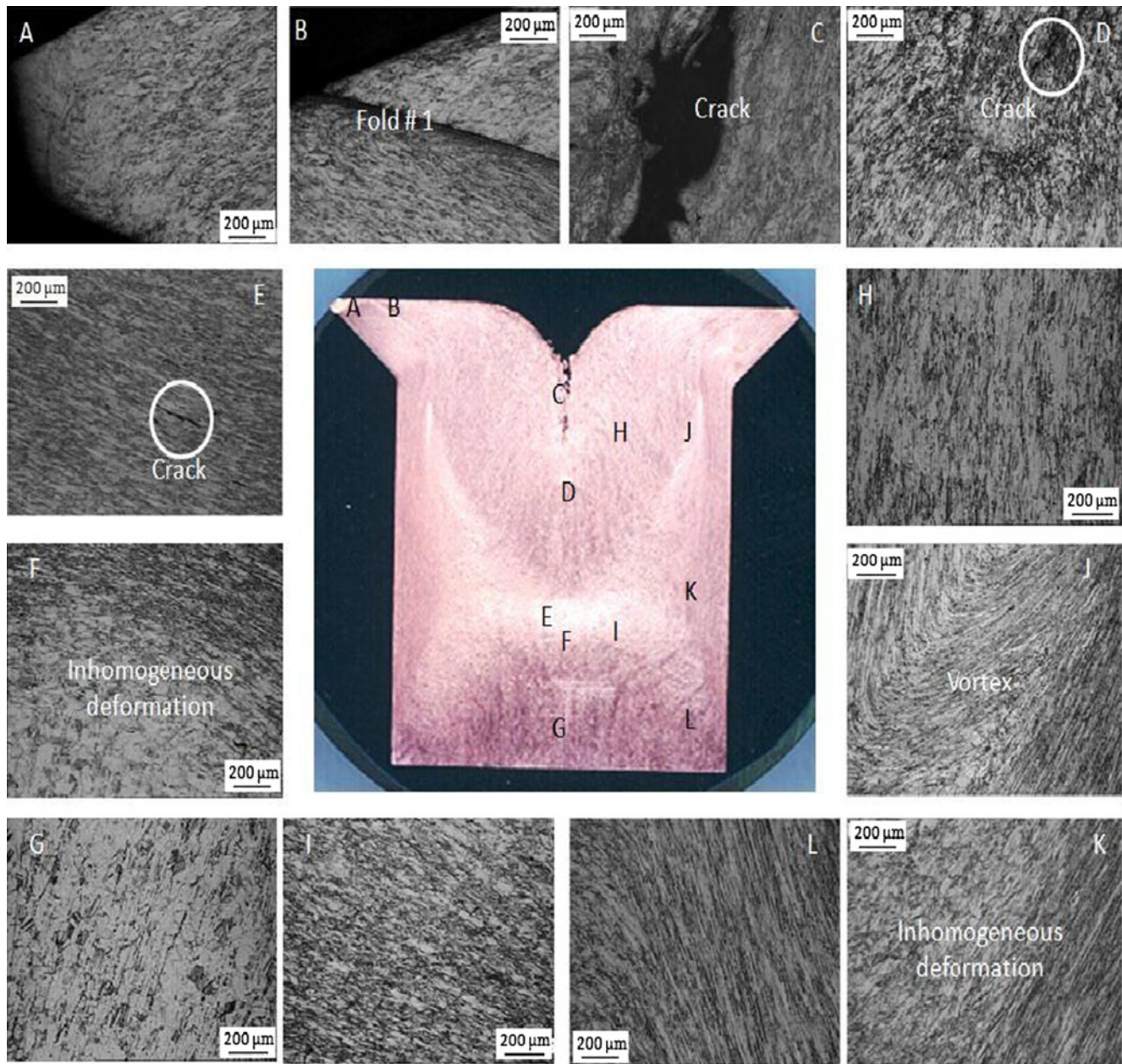
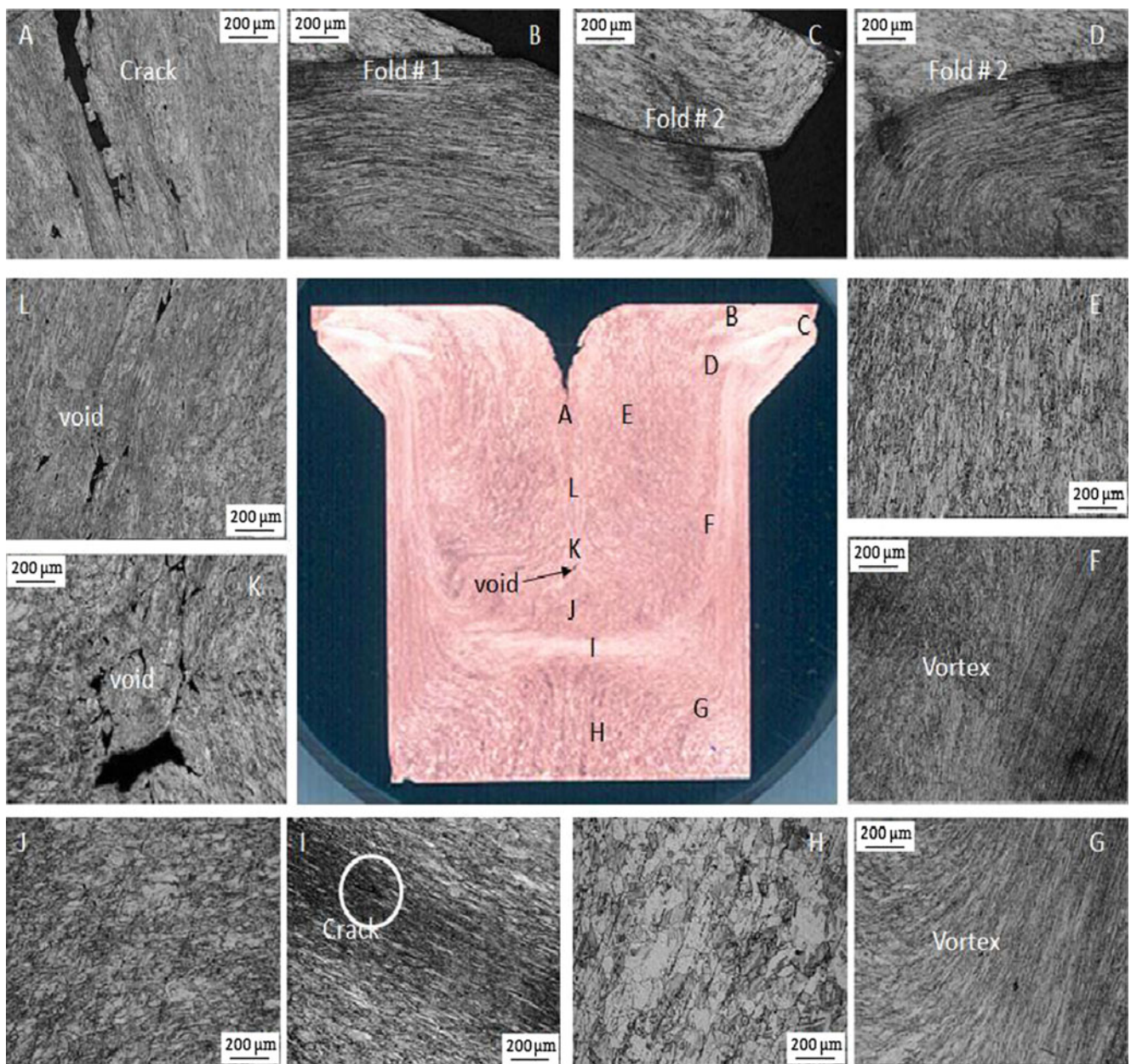


Fig. 8 Microstructure at various locations in the work piece after 2 RUE cycles

penetrate to the centre of the work piece. From the microstructures observed in region-E, H and J (bottom of the work piece), it can be inferred that they have received very less deformation during the extrusion stage.

The microstructure obtained at various locations in the work piece subjected to 2 RUE cycle is shown in Fig. 8. Region-A has experienced a fairly homogeneous deformation, however in region-B a fold is observed. The grains can be seen to be oriented in different directions above and below the fold. The fold is formed during the upsetting stage of second RUE cycle as shown in Fig. 5. When the upsetted material with fold is extruded, only the material below the fold experiences deformation and hence oriented

along the extrusion direction. In region-C and D located below the axial hole, cracks or voids oriented along the extrusion direction can be seen in the work piece. These cracks or voids are created due to axial hole formation during the extrusion process. From Fig. 4a–e and Fig. 8, it can be seen that with increasing RUE cycles, the axial hole or funnel penetrates further deep in to the sample. As the axial hole or funnel penetrates, the surfaces on either side of the groove are squeezed together. As these surfaces do not contact each other completely, voids or cracks are created in the work piece. Cracks can also be seen in region-E, these cracks are oriented perpendicular to the extrusion direction. In region-J which is located near the rim of the work piece,



**Fig. 9** Microstructure at various locations in the work piece after 3 RUE cycles

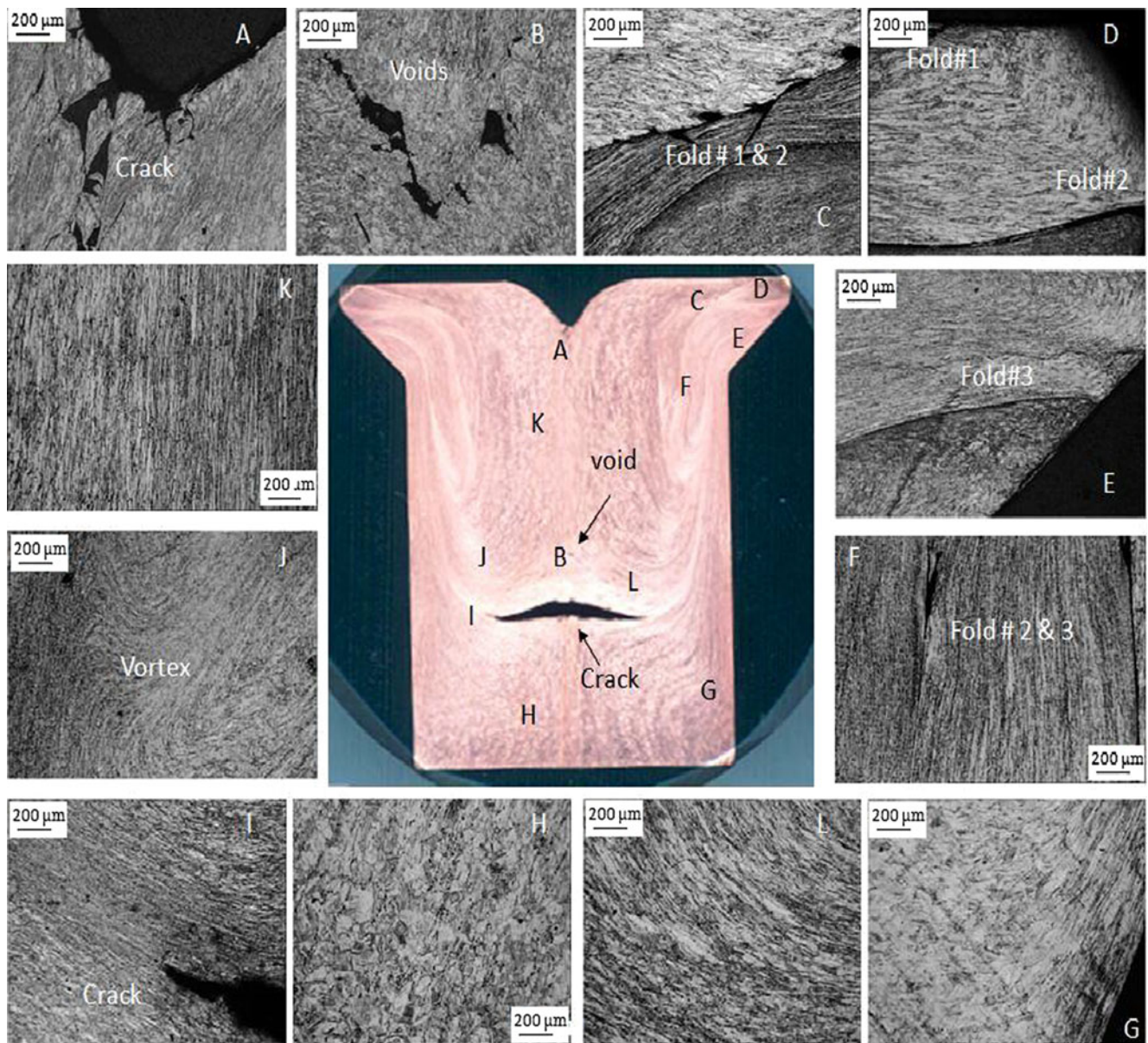


the material experiences severe deformation and a vortex in grain flow can also be observed. The material experiences inhomogeneous deformation in region-K where a portion of the material close to the rim experiences severe deformation while the other part receives very less deformation. A similar microstructure is observed in region-F. Region - E and I have experienced severe deformation.

Cracks and voids are also observed below the axial hole in regions-A, L and K in the work piece subjected to 3 RUE cycles (Fig. 9). Two folds, one in region-B and the other in region-C can be observed in the work piece. The first fold in region-B is created during the upsetting stage of second RUE cycle whereas the second fold in region-C is formed during the upsetting stage of third RUE cycle [19]. Vortex

in the flow of grains can be also seen in region-D, F and G. The vortex in the grain flow can be attributed to the formation of multiple folds. Cracks oriented along the horizontal direction can be seen in region-I.

The microstructure obtained at various locations in the work piece subjected to 4 RUE cycles is shown in Fig. 10. Three folds corresponding to each upsetting stage (excluding the first) can be seen in the wedge shaped region (region-C, D and E). Cracks can also be seen in the folded regions. A large crack oriented perpendicular to the extrusion direction is observed in the material. The cracking of work piece can be attributed to growth and coalescence of cracks or voids that originate from the extrusion defect - axial hole or funnel. The surfaces on either side of the



**Fig. 10** Microstructure at various locations in the work piece after 4 RUE cycles

groove (axial hole or funnel) formed during first RUE cycle are squeezed together during subsequent extrusion cycles. As these surfaces do not contact each other completely, voids or cracks are created in the work piece. As the axial hole or funnel penetrates further deep in to the sample during subsequent RUE cycles, the cracks or voids are transported to the center of the work piece. During the upsetting stage of subsequent RUE cycles, these voids get compressed and elongated. Thus as the number of cycles increases, sufficient voids or cracks are transported to the central region, they get coalesced during the upsetting stage and get opened up during the extrusion stage. The vertical orientation of cracks or voids along the axial hole, the location of the crack (horizontal crack in Fig. 10) in the severely deformed region oriented perpendicular to the extrusion direction substantiates the above observation.

**Modified RUE die design and experiments on CP Cu**

More recently, Balasundar and Raghu [22] 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 i.e., height (h) and die angle ( $\theta$ ) of Volume  $V_2$  in an RUE to avoid the extrusion defect are

$$h \geq \frac{D_f}{2} \tag{1}$$

$$\theta \geq \tan^{-1} \left( \frac{r}{h} \right) = \tan^{-1} \left( \frac{\frac{D_o - D_f}{2}}{\frac{D_f}{2}} \right) = \tan^{-1} \left( \frac{D_o - D_f}{D_f} \right) \tag{2}$$

$D_o$  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 [16, 17], 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. 11 is being proposed to process bulk materials. It can be seen that in the modified RUE die design, the height of volume  $V_2$  is greater than half the diameter of  $V_3$  as per Eq. 1. Further, to avoid the fold formation, appropriate fillet radii have been provided at the intersection point of two volumes. The modified die was designed to process a similar dimension CP Cu sample (20 mm diameter by 30 mm height) in order to provide direct comparison of the results. Using this modified die design, CP Cu samples were subjected up to 4 cycles of RUE by following the same procedure discussed earlier in section RUE experiments.

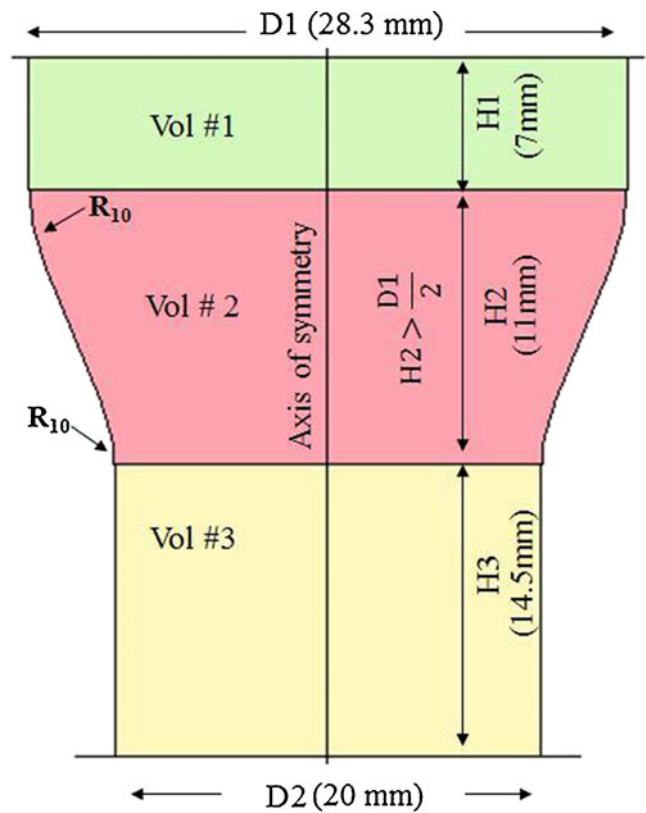


Fig. 11 Modified RUE die design

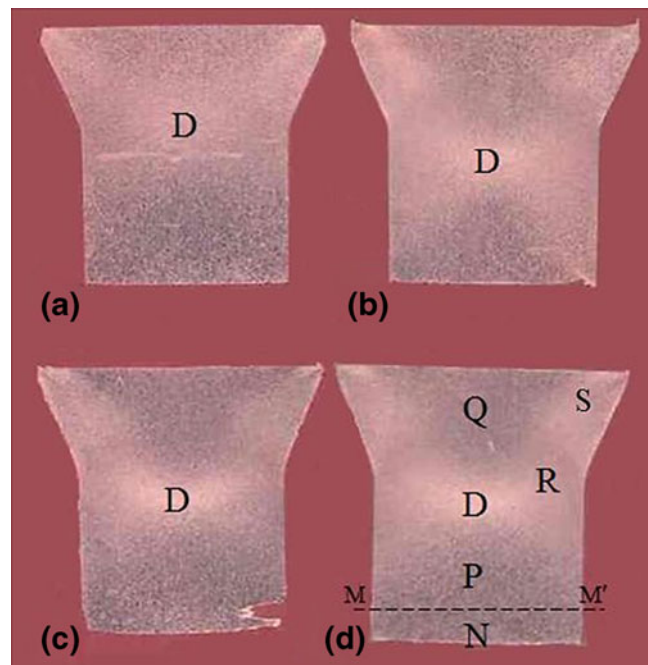


Fig. 12 Macrostructure of CP Cu samples subjected to (a) 1 (b) 2 (c) 3 and (d) 4 cycles of RUE using the modified die design

Macro and microstructure obtained using the modified die design

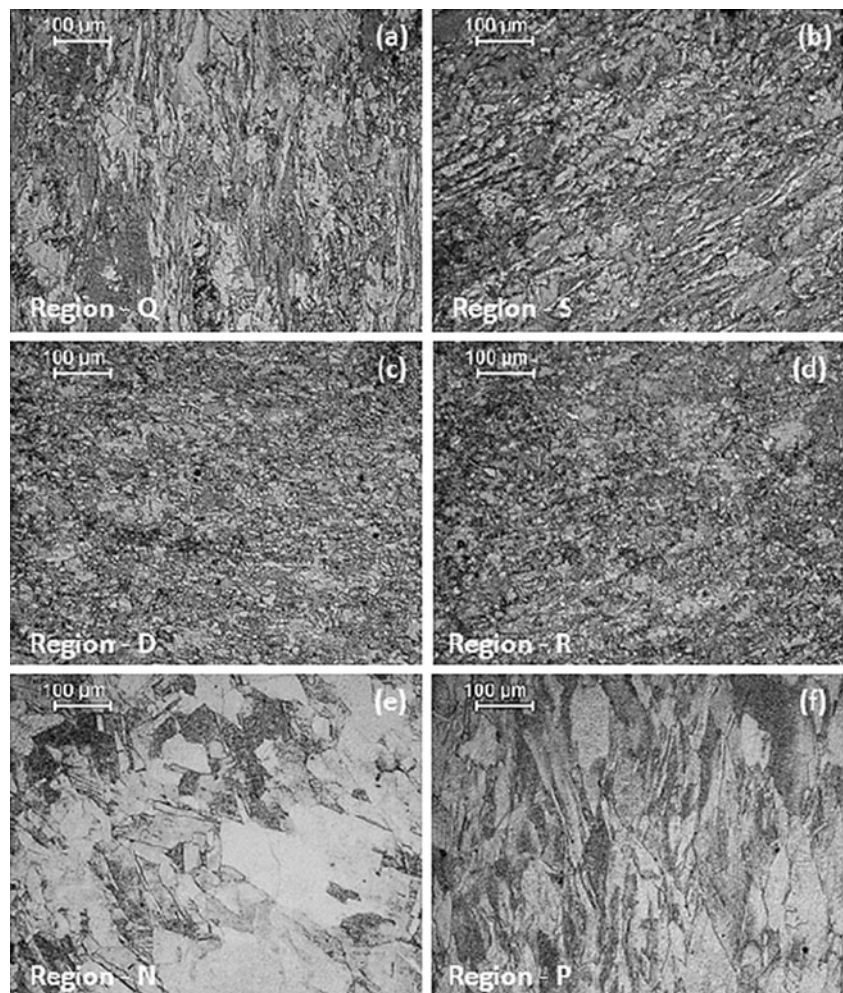
The macrostructure obtained after subjecting CP Cu samples up to 4 cycles of RUE using the modified die design is shown in Fig. 12. The absence of the extrusion defect - axial hole/funnel and the upsetting defect – fold/lap can be readily seen. The microstructure obtained across the sample that had been subjected up to 4 RUE cycles is shown in Fig. 13. The microstructure observed at various locations (Fig. 13) not only concurs well with the deformation pattern (Fig. 12) but also represents the mechanism of grain refinement that is typical of severe plastic deformation as reported by various researchers [1, 24–26]. Though a significant amount of grain refinement can be readily observed at region-D and region-R at the end of 4 RUE cycles, there is a large variation in the grain size across the cross-section of the sample. In the region P, the grains can be seen to be elongated along the extrusion direction whereas in region Q and S, a duplex microstructure containing elongated grains and small globular grains

can be seen. In region-N (below the line MM' marked in Fig. 13), the microstructure at the end of 4 RUE cycles still resembles the as received microstructure. This implies that this region has not received much deformation. A detailed description on the strain achieved across the cross-section of the sample is explained elsewhere [23]. Homogenous distribution of grain size across the sample cross-section can be achieved either by increasing the amount of deformation further i.e., increasing the number of cycles as observed in other SPD processes [24–26] or by optimizing the processing sequence. For e.g., one can initiate the repetitive process with extrusion instead of upsetting or one can also rotate the sample between cycles [27] to achieve better homogeneity.

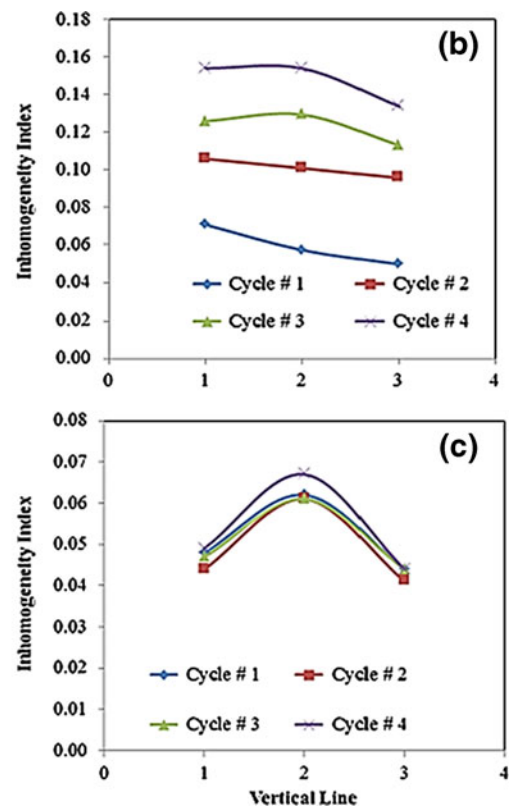
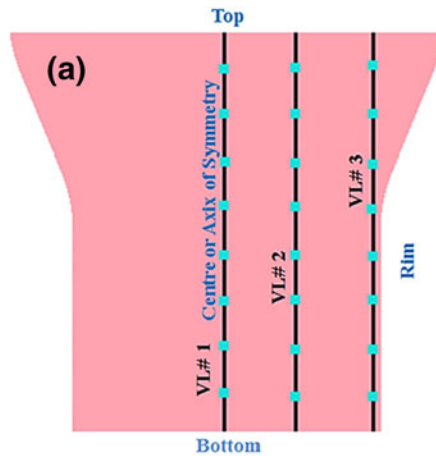
### Deformation homogeneity

The homogeneity is generally evaluated using an inhomogeneity index [19, 28, 29]. The inhomogeneity index or coefficient of variance is defined as the ratio between the

**Fig. 13** Microstructure at various locations in the CP Cu sample subjected to 4 cycles of RUE using the modified die design



**Fig. 14** (a) Vertical line with location of microhardness measurement. Variation of deformation inhomogeneity index along the vertical lines in the samples subjected to RUE using (a) original die design (b) modified die design



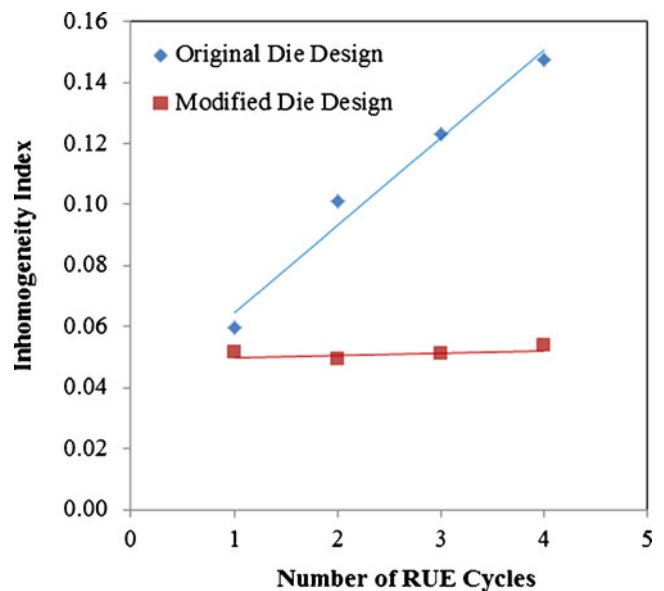
standard deviation and the average value of strain or hardness as shown in the Eq. 3 below.

$$CV_{mHv} = \frac{Stdev.mHv}{Avg.mHv} \quad (3)$$

where,  $CV_{mHv}$  is the coefficient of variance of microhardness,  $stdev\ mHv$  is standard deviation of microhardness and  $Avg.\ mHv$  is the average microhardness along a cross section. A lower value of the index implies better homogeneity. In order to estimate the inhomogeneity index, microhardness was estimated along three vertical lines (VL#1, VL#2 and VL#3) across the sample cross-section as shown in Fig. 14a. Along each vertical line, eight locations were chosen at equidistance and a minimum of three readings were taken at each location to obtain the average microhardness. Using the measured microhardness values, the inhomogeneity index was estimated.

The inhomogeneity index along the three vertical lines in the samples subjected to RUE using the original and modified die design are shown in Fig. 14b and c respectively. It can be seen that in case of samples processed using the original die design (Fig. 14b), along the horizontal direction i.e., from the centre of the sample (VL#1) to rim (VL#3) the inhomogeneity decreases irrespective of RUE cycle. However, the inhomogeneity index along any vertical line increases with increasing number of RUE. In case of the samples processed using the modified die design (Fig. 14c), the inhomogeneity index

has a higher value along the vertical line VL#2 when compared to VL#1 and 3 for any given RUE cycle. Similar to that observed in the samples processed with the original die design, the inhomogeneity index was found to increase with increasing RUE cycle along all the vertical lines. However, the rate of increase in inhomogeneity was found



**Fig. 15** Inhomogeneity index measured across the cross-section of the samples subjected to various RUE cycles using the original and modified die design

to be high with the original die design. To gain further insight, the inhomogeneity index was evaluated by using the microhardness values measured across the entire cross-section of the sample. The inhomogeneity index so evaluated across the cross-section of the sample is shown in Fig. 15. It can be seen that with the original die design, the inhomogeneity increases drastically with increasing number of RUE cycles. On the other hand with the modified die design, increasing RUE cycles has only a marginal effect on the inhomogeneity. This clearly shows that for any given RUE cycle, the modified die design imparts better homogeneity when compared to the original die design. The improved homogeneity can be attributed to the absence of folds as well as to the change in deformation pattern and strain distribution across the sample cross-section due to the design change (volume  $V_2$ ) in the modified RUE die.

## Summary

Based on the RUE experiments carried out on CP Cu using the existing die design and the modified die design it can be inferred that, the existing RUE die design that is being used by researchers is not appropriate for processing bulk materials as it imparts not only inhomogeneous deformation but also defects such as fold and axial hole. The formation of these defects (folds and axial hole) can be attributed to the improper design of volume  $V_2$ . The modified die design proposed based on the minimum height required for volume  $V_2$  has been proved to be useful in not only avoiding the defects but also in improving the homogeneity of the process.

## References

- Valiev RZ, Islamgaliev IV, Alexandrov IV (2000) Bulk nanostructured materials from severe plastic deformation. *Prog Mater Sci* 45:103–189
- Alexander DJ (2007) New methods for severe plastic deformation processing. *J Mater Eng Perfor* 16(3):360–374
- Azushima A, Koop R, Korhonen A, Yang DY, Micari F, Lahoti GD, Groche P, Yanagimoto J, Tsuji N, Rosochowski R, Yanagia A (2008) Severe plastic deformation processes for metals. *CIRP Ann-Manuf Technol* 57:716–735
- Zrnik J, Dobatkin SV, Mamuzic I (2008) Processing of metals by severe plastic deformation-Structure and mechanical properties respond. *Metallurgia* 47(3):211–216
- Segal VM (1995) Materials processing by simple shear. *Mater Sci Eng A* 197:157–161
- Segal VM (2002) Severe plastic deformation: simple shear versus pure shear. *Mater Sci Eng A* 338:331–344
- Cheng Z-H, Cheng Y-Q, Xia W-J (2007) Effect of equal-channel angular rolling pass on microstructure and properties of magnesium alloy sheets. *Mater Manuf Process* 22:51–56
- Richert M, Liu Q, Hansen N (1999) Microstructural evolution over a large strain range in aluminium deformed by cyclic-extrusion-compression. *Mat Sci Eng A* 260:275–283
- Zhilyaev AP, Langdon TG (2008) Using high-pressure torsion for metal processing: fundamentals and applications. *Prog Mat Sci* 53:893–979
- Saito Y, Utsunomiya H, Tsuji N, Sakai T (1999) Novel ultra-high straining process for bulk materials - development of accumulative roll bonding process. *Acta Mater* 47:579–583
- Ji YH, Park JJ (2009) Development of severe plastic deformation by various asymmetric rolling processes. *Mat Sci Eng A* 499:14–17
- Zhu YT, Jiang HG, Huang J, Lowe TC (2001) A new route to bulk nanostructured materials. *Metall Mater Trans A* 32:1559–1562
- Yoon SC, Krishnaiah A, Chakkingal U, Kim HS (2008) Severe plastic deformation and strain localization in groove pressing. *Comp Mater Sci* 43:641–645
- Aizawa T, Tokimutu K (1999) Bulk mechanical alloying for productive processing of functional alloys. *Mater Sci Forum* 312–314:13–22
- Hu L, Li Y, Wang E, Yu Y (2006) Ultrafine grained structure and mechanical properties of a LY12 Al alloy prepared by repeated upsetting-extrusion. *Mat Sci Eng A* 422:327–332
- Kalpakjian S, Schmid SR (2003) Bulk deformation processes in manufacturing processes for engineering materials, 4th edn. Pearson Education (Singapore) Pte.Ltd, India, pp 300–312
- Dieter GE (1998) Extrusion, chapter 18. In: *Mechanical metallurgy*. McGraw-Hill, NY, pp 616–634
- Kraft FF, Gunasekera JS (2004) Conventional hot extrusion. In: Semiatin SL (ed) *ASM Handbook Vol14A Metal working - Bulk forming*. ASM International Material Park, Ohio, pp 421–434
- Balasundar I, Raghu T (2010) Deformation behaviour of bulk materials during repetitive upsetting extrusion (RUE) process. *Int J Mater Form* 3:267–278
- Saanouni K (2006) Virtual metal forming including the ductile damage occurrence - Actual state of art and main perspectives. *J Mater Proc Technol* 177:19–25
- Saanouni K (2004) Numeric prediction of discontinuous central bursting in axisymmetric forward extrusion by continuum damage mechanics. *Comput Struct* 82:2309–2332
- Balasundar I, Raghu T (2010) Investigations on the extrusion defect - Axial hole or funnel. *Mater Des* 31:2994–3001
- Balasundar I, Raghu T (2011) Deformation behaviour of commercial pure copper during repetitive upsetting – extrusion using a modified die design. *Kovove Mater* 49:1–13
- Valiev RZ, Langdon TG (2006) Principles of equal channel angular pressing as processing tool for grain refinement. *Prog Mater Sci* 51:881–981
- Lowe TC, Valiev RZ (2000) Producing nanoscale microstructures through severe plastic deformation. *J Metals* 200:27–28
- Kommel L, Hussainova I, Volobueva O (2007) Microstructure and properties development of copper during severe plastic deformation. *Mater Des* 28:2121–2128
- Balasundar I, Raghu T (2011) On the homogeneity of RUE and REU processing routes, Article No. 476, NMD-ATM 2011, Indian Institute of Metals, 13–16 November 2011, Hyderabad, India
- Balasundar I, Raghu T (2010) Effect of friction model in numerical analysis of equal channel angular extrusion process. *Mater Des* 31:449–457
- Patil Basavaraj V, Chakkingal Uday, Prasanna Kumar TS (2009) Study of channel angle influence on material flow and strain inhomogeneity in equal channel angular pressing using 3D finite element simulation. *J Mater Process Technol* 209:89–95