Optimization of Die Geometry for Tube Channel Pressing

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ABSTRACT

Since tubes have numerous industrial applications, many attempts have focused on the Severe Plastic Deformation (SPD) processes of tubes. Tube Channel Pressing (TCP) is an attractive process since it can be used for processing different sizes of tubes. However, more attempts are needed to improve the outcomes of TCP. For example, imposing of greater strain besides reductions of strain heterogeneity are the challenges of this process. This work is aimed to optimize the die geometry of TCP in order to increase the imposed strain as well as to decrease strain heterogeneity through an FEM simulation method verified by experiment. The results showed that the increase of die curvature radius causes the decrease of imposed plastic strain and the increase of strain heterogeneity. In addition, the minimum amount of die convex height for imposing of reasonable strain through TCP was calculated considering tube thickness and channel angle. Besides, the optimum die geometry is recommended in order to minimize the strain heterogeneity.

1-Introduction

Imposing of Severe Plastic Deformation (SPD) is considered as an attractive method for improvement of mechanical properties and grain refinement of metallic materials. For example, Equal Channel Angular Pressing (ECAP) for rods, High Pressure Torsion (HPT) for thin disks and Accumulative Roll Bonding (ARB) for sheets are well-known SPD processes developed during the past decades [1-4]. Recently, a notable attention is given to SPD of tubes and different works have focused on the development of SPD processes for tube based on ARB, HPT and ECAP [4-11]. In comparison with other processes, SPD processes for tube developed based on ECAP have multiple benefits such as: less limitation for dimensions of tubes, the need for less complicated machinery device and imposing a relatively homogenous plastic strain. Examples of these processes can be presented as: tubular ECAP [7-8], Tube Channel Pressing (TCP) [9-11] and Tubular Channel Angular Pressing (TCAP) [12-13]. As an illustration, when a tube is processed by TCP, the tube passes a bottleneck region which causes a multi-stage shear straining besides a hoop straining as shown in Fig. 1 [9-10]. Although few studies have focused on the effect of die/mandrelgeometry on the deformation behavior of tubes through TCP [10-11, 14], some aspects of TCP die geometry have remained less considered. As an illustration, previous studies have shown considerable heterogeneity of strain imposed by this process which is not desirable for an SPD process. Besides, the effect of die geometry on the imposed strain through TCP has not been thoroughly studied yet. Therefore, more attempts are needed to decrease the strain

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heterogeneity and to analyze the amount of strain imposed by this process.
The aim of this work is to decrease the strain heterogeneity and increase the imposed strain of TCP process using new die geometry. For this purpose, FEM simulations are applied to predict the deformation behavior of Al-1.7Fe-0.9Si-0.5Cu tube through processing by TCP dies which are designed using different geometries. Besides, experimental examinations are accomplished using a TCP die to investigate accuracy of simulation results. Comparing the results of simulation and experiment, the geometry of die is optimized to minimize the strain heterogeneity and to impose a greater strain.

2- Analysis and selection of parameters for TCP

Fig. 1 shows a schematic illustration of a new geometry of TCP process and its die/mandrel geometrical parameters. As can be seen, processing of a tube by the new geometry of TCP causes four stages of shear straining of tube wall accompanied by its hoop straining. Considering constant dimensions of a tube, geometrical variables of TCP process are as follows: the channel angle ($\Theta_{channel}$), the length of mandrel cave ($L_{mandrel}$), the curvature radiuses of die/mandrel(R), the height of die convex (Δr_{die}) and the depth of mandrel cave($\Delta r_{mandrel}$). In this work, the inner and outer diameter of the used tube is 44.4 and 50.8 mm, respectively. This clarifies a tube thickness (t) of 3.2 mm. Considering previous studies, $\Theta_{channel}$ and L_{die} are constantly considered as 150° and0 mm while $L_{mandrel}$ is considered as 2 mm regarding the thickness of used tube [10-13]. In addition, to prohibit thinning of the tube over TCP as much as possible, the cross section area of tube in the middle of the bottleneck region must be saved. Therefore, the depth of mandrel cave ($\Delta r_{mandrel}$) is calculated according to Eq. 1 [14]:

$$r_{Ot}^2 - r_{It}^2 = (r_{Ot} - \Delta r_{die})^2 - (r_{It} - \Delta r_{mandrel})^2 \quad (1)$$

where r_{Ot} is the outer radius of the tube and r_{It} is the inner radius of the tube. Regarding what was mentioned above, one die geometry can be characterized by two independent geometrical variables: curvature radius (R) and die convex height (Δr_{die}). As it was shown before, the corner of channel of TCP die should be smooth to prevent the stress concentration on die as well as to prevent deviated shapes of tube after the process [11].

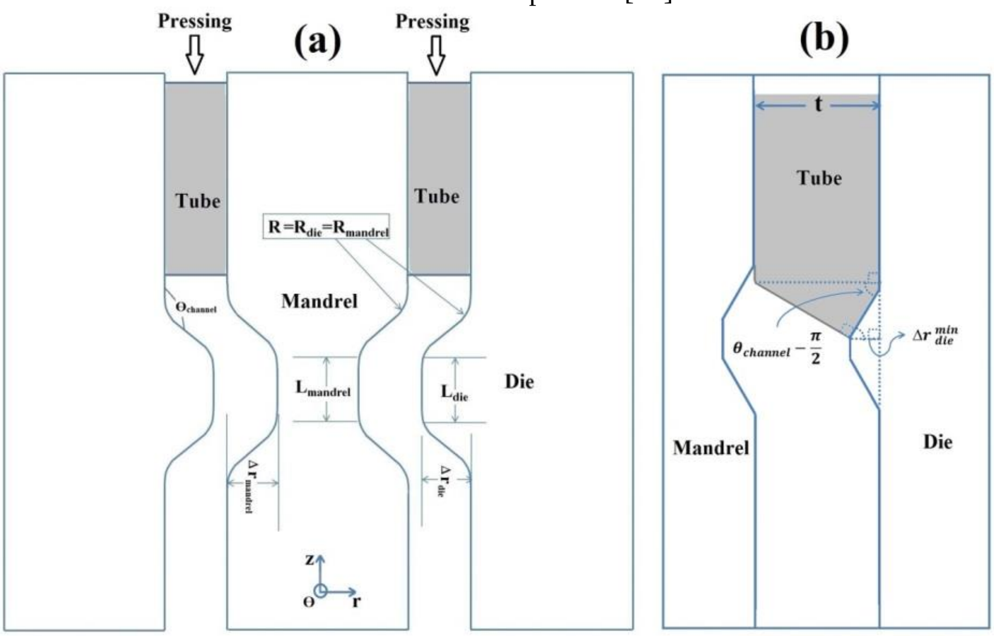

Fig. 1. (a) Schematic illustration ofthe new geometry of TCP and its geometrical variables. (b) The illustration of minimum of $\Delta r_{die}$for occurrenceof subsequent shear through TCP

On the other hand, selection of a large curvature radius causes the occurrence of shear-banding through TCP which increases micro-scale strain heterogeneity [15]. Regarding these limitations, six different amounts of 0.8, 1.6, 2.4, 3.2, 4 and 4.8 mm (≈ 0.25, 0.5, 0.75,1, 1.25 and 1.5 times of tube thickness) are considered for R of TCP to evaluate the effect of this parameter on the deformation behavior of tube.

Considering the ideal geometry of TCP shown in Fig. 1 (b), one may relate the minimum of Δr_{die} for occurrence of subsequent shear in the tube wall to $\Theta_{channel}$ and t as below:

$$\Delta r_{die}^{min} = t\cos^2\left(\theta_{channel} - \frac{\pi}{2}\right) \quad (2)$$

By substitution of $\Theta_{channel}$ and t equal to 150° and 3.2 mm, Δr_{die}^{min} is calculated as 0.8 mm (0.25t). It is also noteworthy that by considering the ideal shear straining and hoop straining through TCP, the total equivalent plastic strain on each selected element of the tube wall can be analytically calculated as:

$$\varepsilon = 1.15\left\{4Cot\left(\frac{\Theta_{channel}}{2}\right) + 2Ln\left(\frac{r_{tube}}{r_{bottleneck}}\right)\right\} \quad (3)$$

where r_{tube} and $r_{bottleneck}$ are the radiuses of the selected tube wall element before process and in the middle of bottleneck zone, respectively. According to Eq. (3), the amount of imposed strain increases by the increase of Δr_{die}(see Fig. 1 & Eq. (1)). It is notable that greater hoop strains are imposed on the inner side of the tube in comparison to that imposed on the outer side of the tube since the relative variation of the inner radius of the tube through TCP is greater than the relative variation of the outer radius of the tube according to Eq. (1). Moreover, by an increase of Δr_{die}, the relative increase of $\Delta r_{mandrel}$ is greater than the relative increase of Δr_{die} according to Eq. (1). This implies that the heterogeneity of hoop strains increases by the increase of Δr_{die} according to Eq. (3).

Although the effect of Δr_{die} on the deformation behavior of tube was briefly explained in the previous paragraph, it must be noted that this analysis considers the ideal shear and hoop straining through TCP which occurs by the selection of a sharp channel corner. Therefore, this analysis may not be true for a real TCP die which has a smooth channel corner. In other words, since the channel corner of a real TCP die is relatively smoothed by a curvature radius of R, the effect of Δr_{die} on the deformation behavior of tube through TCP may be dependent on R. In this regard, seven different amounts of 0.5, 0.9,1.3, 2.1, 3.1, 4.1 and 5.1 mm (≈ 0.16, 0.28, 0.41, 0.65, 0.97, 1.28 and 1.6 times of t) are considered for Δr_{die} to investigate the effect of this parameter on the deformation behavior of the tube through TCP process.

3- Simulationprocedure

Deformation behavior of Al-1.7Fe-0.9Si-0.5Cu alloy tube during processing by different TCP dies is simulated by Abaqus 6.13 software using a 2D axisymmetric dynamic explicit FEM model based on Lagrangian formulation. The adaptive meshing method is applied to decrease the mesh distortion through simulation. Die and mandrel are meshed using the CAX3 and CAX4R elements which respectively consist of 3 and 4 nodes. The mesh sizes for these parts are as follows: 7 mm for the surfaces which have no contact with the specimen, 2 mm for the surfaces which have contact with the specimen out of the bottleneck zone and 0.5 mm for the surfaces which have contact with specimen inside of the bottleneck zone.The tube is meshed using 0.5×0.5 mm CAX4R elements.To investigate the mesh sensitivity of applied simulation method, one simulation was carried out in which the mesh size was half of the mentioned amounts. Results of this simulation have shown a negligible difference in comparison with the results of its counterpart which have typical mesh size. For example, the difference in the calculated equivalent plastic strain was less than 5%. The interaction between the die, mandrel and specimen surfaces is defined by the penalty contact method and the sliding friction coefficient is considered equal to 0.01.Voce relation is used for extrapolation of flow stress vs. plastic strain curve since this relation can accurately predict this curve for aluminum alloys subjected to extensive plastic strains [16-17]. The saturation flow stress of voce relation is considered as 200 MPa regarding previous works on SPD of similar alloys [18].

4- Experiments and validation procedure

The tube is annealed for 45 min. in 753 °K to eliminate the probable work hardening of material through previous tube forming process.

Then, a tensile test was performed to obtain flow stress vs. plastic strain curves for the used material. A TCP die is manufactured using the *R* of 3.2 mm and Δr_{die} of 3.1 mm and it is used for experimental studies on the deformation behavior of the tube. As can be seen in Fig. 2, the contact surfaces of die/mandrel with specimen are fully polished to decrease the friction coefficient as much as possible. In addition, MoS_2 is used for lubrication of the die, mandrel and specimen surfaces. In order to examine the capability of simulation procedure to estimate the needed deformation load of TCP, experimentally obtained load-displacement curve through TCP of used tube is compared with its simulated counterpart. Besides, in order to study the ability of simulation procedure to estimate the imposed plastic strain, variations of the Vickers hardness and the simulated imposed plastic strain through tube wall thickness are compared. The Vickers hardness is obtained using 2N load along the thickness of TCP processed tube by a step distance of 0.5 mm.

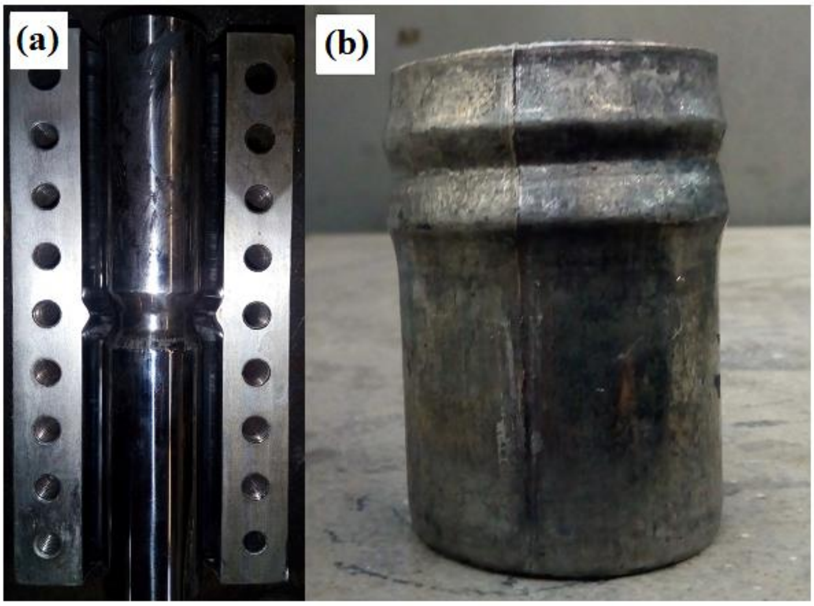

Fig. 2. (a) Manufactured TCP die considering the new geometry. (b) The specimen processed using manufactured die

5- Results and discussion

Fig. 3 (a) shows the simulated deformation behavior of tube during processing by TCP using the manufactured die. As can be seen, three different regions along tube length can be characterized considering the distribution of imposed strain. At the bottom of the tube, the unsteady-state deformed region exists which has freely passed the bottleneck zone because of little frictional contact with the die/mandrel surfaces. Since this region of the processed tube does not completely follow the channel route, the amount of imposed strain on this region is relatively lower and the distribution of strain is heterogeneous comparing with its upper counterpart. The middle region of TCP processed tube is the steady-state deformed region which has been almost in full contact with the die/mandrel surfaces during the deformation process. As can be seen, a remarkable and relatively homogenous strain is imposed on this region of the tube wall. The upper region has been remained in bottleneck zone of the die after the process and has not finished the process. Therefore, the amount of imposed strain on this region is relatively lower. It is also notable that since the next pass of TCP is imposed from the bottom of tube to upward, the unsteady-state deformed region and the remained region in bottleneck zone nearly replace each other in the next pass.This means limited involvement of these regions in the process. Thus, it is clear that the only usable section of a TCP processed tube is the steady-state deformed region whereas a considerable plastic strain is imposed almost homogeneously. Therefore, analysis of the imposed strain and the strain heterogeneity is focused on this region. Fig. 3 (b) compares the experimentally obtained deformation load versus displacement through TCP processing using the manufactured die by its simulated counterpart. As can be seen, the general trend of experimentally obtained deformation load follows its simulated counterpart. Fig. 3 (c) compares variation of the Vickers micro-hardness along tube thicknessversus imposed plastic strain through TCP processing estimated by simulation. As can be seen, the Vickers hardness variation trend is comparable with the variation trend of the imposed plastic strain estimated by the simulation. Considering these results, the capability of simulation procedure to estimate both deformation load and imposed plastic strain is verified.

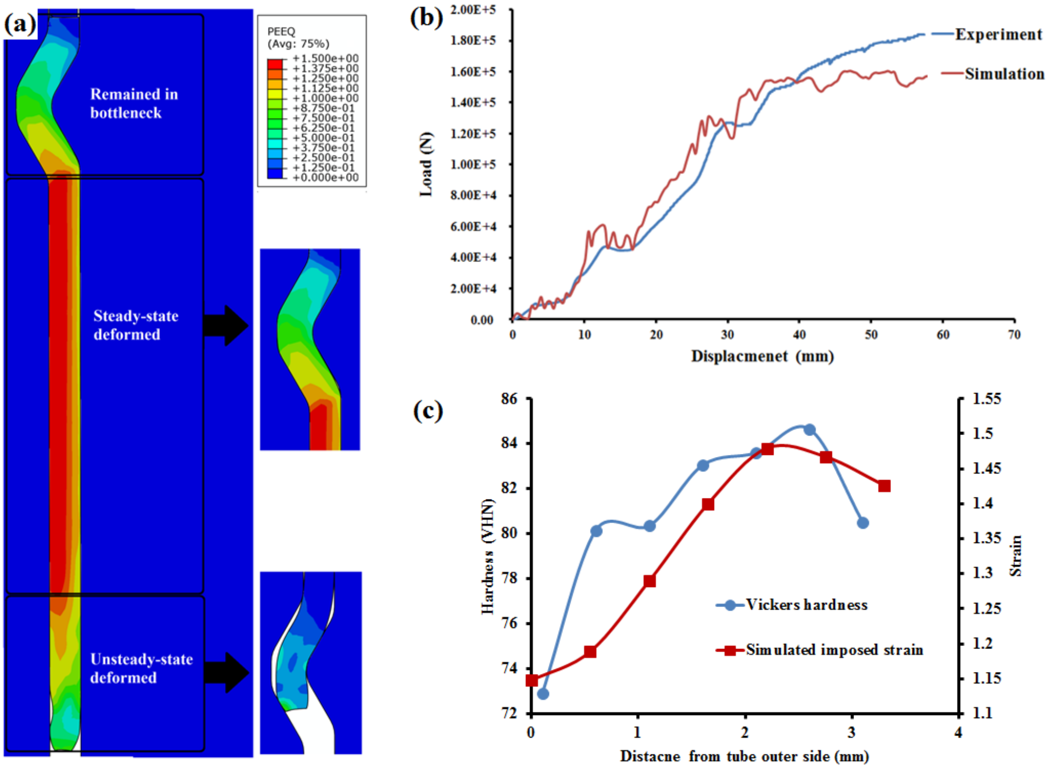

Fig. 3. (a) Illustration of three differently deformed regions throughprocessing bynew geometry of TCP. (b) Comparison of simulation and experiment results for load-displacement curve of TCPprocessing using manufactured die. (c) Comparison ofthe simulated imposed strain andthe Vickers micro-hardness along tube wall thickness after one pass of TCP

Fig. 4 (a) compares the variation of imposed plastic strain by TCP versus the variation of curvature radius (*R*) and convex height of die (Δr_{die}). To obtain an analytical approximation of imposed strain on whole of tube wall, Eq. (3) is applied in which r_{tube} and $r_{bottleneck}$ are considered as the average radiuses of tube before process and in the middle of bottleneck zone, respectively. As can be seen in Fig. 4 (a), the imposed plastic strain decreases by the increase of *R*, which will be discussed later. Moreover, the imposed plastic strain increases by the increase of Δr_{die} which can be attributed to the increase of the imposed hoop strain according to Eq. (3). It is notable that the imposed strain usingΔr_{die} of 0.5mm is much lower than that approximated by Eq. (3). This implies a different deformation behavior of tube using the Δr_{die} of 0.5 mm which will be discussed later. Fig. 4 (b) compares the variation of needed deformation load by variation of *R* and Δr_{die}. As can be seen, the needed deformation load increases by the decrease of R and increase of Δr_{die}. By comparison of Figs. 4 (a) & (b), it is inferred that the variation of needed deformation load and imposed plastic strain through TCP processing is almost similar. Therefore, the increase of deformation load by the decrease of R and the increase of Δr_{die} is mainly attributed to the increase of imposed plastic strain which was mentioned before.

Fig. 5 shows the effect of R and Δr_{die} on "Standard Deviation of strain distribution per unit of average Plastic Strain (SDPS)" which is calculated as follows:

$$SDPS = \frac{\sqrt{\frac{\sum_{i=1}^{n}(\varepsilon_i-\bar{\varepsilon})^2}{n}}}{\bar{\varepsilon}} \quad (4)$$

where n is the number of nodes along tube thickness, $\bar{\varepsilon}$ is the average of imposed plastic strain and ε_i is the imposed strain on each node.

It is notable that the nodes placed on boundary of tube are considered with coefficient of 0.5 in calculation of $\bar{\varepsilon}$ and SDPS. As can be observed in Fig. 5, the SDPS generally increases by increase of R. For instance, the lowest SDPS can be achieved by selection of R equal to 0.8-1.6 mm (0.25t-0.5t). In addition, variation of SDPS versus Δr_{die} has two different trends. While at the first step the SDPS decreases by the increase of Δr_{die}, at the second step, it increases by the increase of Δr_{die}. It is also noteworthy that the decrease of SDPS in the first step has two different rates: it falls drastically by the increase of Δr_{die} from 0.5 mm to 0.8 mm while it decreases slightly by the increase of Δr_{die} from 0.8 mm. This implies a different deformation behavior of tube through TCP processing when Δr_{die} of 0.5 mm is used as discussed later.

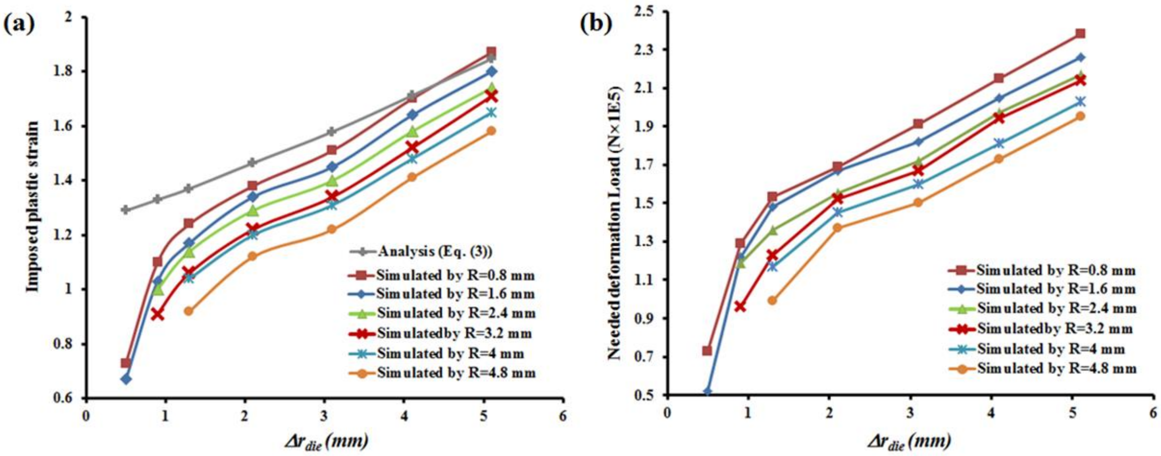

Fig. 4. The effect of Δr_{die} and R on: (a) Imposed plastic strain and (b) needed deformation load through TCP processing

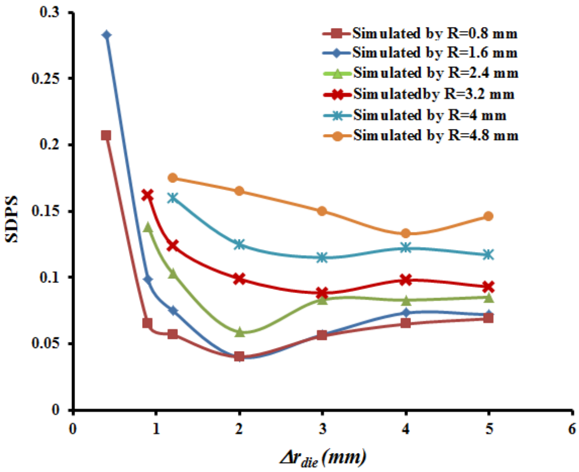

Fig. 5. The effect of Δr_{die} and R on variation of the SDPS through TCP processing

Considering what was stated above, one can infer that the increase of R decreases the imposed plastic strain and needed deformation load while it increases the strain heterogeneity. Similarly, it has been reported that the increase of die corner radius of the ECAP process causes the decrease of imposed plastic strain and the increase of strain heterogeneity. This effect has been attributed to occurrence of bending instead of pure shear through the process by the increase of die corner radius [19-21]. As can be seen in Figs. 4 & 5, the effect of R on the strain heterogeneity is more severe than its effect on the imposed plastic strain. As an illustration, while the increase of R from 1.6 mm to 4.8 mm causes a few ten percents decrease of the imposed strain, it causes a few times increase of the SDPS. This extensive increase of strain heterogeneity causes heterogeneity of the properties of the processed tube which is undesirable. Therefore, it seems that the selection of R about 0.25t-0.5t is more rational to obtain a relatively homogenous plastic strain. As shown in Figs. 4 and 5, when Δr_{die} of 0.5mm is selected, the imposed strain is remarkably lower while SDPS is impressively greater in comparison with the other counterparts using greater amounts of Δr_{die}. As it was mentioned before, the Δr_{die}^{min} for occurrence of subsequent shear in tube wall through TCP processing can be analytically defined as 0.8 mm. Thegreater SDPS and the lower imposed strain on tube wall usingΔr_{die} of 0.5 mm for TCP processing shown by simulations verify accuracy ofthis definition of Δr_{die}^{min}. For explanation, when Δr_{die} is selected less than Δr_{die}^{min}, the occurrence of shear in tube wall is incomplete. This decreases the imposed strain and increases the SDPS. Besides, although it was expected that the increase of Δr_{die} results in the increase of SDPS, this effect only occurs after a specific Δr_{die}. For explanation, there is an optimum amount of Δr_{die} in which the SDPS is minimized and this optimum amount is dependent of R. As an illustration, when R of 4.8 mm is selected, the SDPS is minimized using Δr_{die} of 4.1 mm (1.28t). In contrast, when R of 0.8-2.4 mm is selected, the SDPS is minimized using Δr_{die} of 2.1 mm (0.65t). Considering what was mentioned above, one can propose that the geometry of TCP die can be optimized by the selection of R and Δr_{die}respectively about*0.25t-0.5t* and *0.65t* which causes obtaining of the lowest strain heterogeneity besides a remarkable imposed plastic strain.

6- Conclusion

Considering the results of this work, it can be concluded:

1- The applied simulation method can be used to predict the imposed plastic strain as well as needed deformation load through TCP processing.
2- Increase of die curvature radius (R) from 0.25-0.5 time of tube thickness (t) causes the decrease of imposed plastic strain and needed deformation load while it increases the strain heterogeneity.
3- Considering the channel angle ($\Theta_{channel}$) to be equal to 150°, the minimum amount of die convex height (Δr_{die}) for the occurrence of subsequent shear through TCP processing is obtained to be equal to 0.25t as illustrated in Eq. (2).
4- The optimum amount of Δr_{die} is strongly dependent on R. For instance, by selection of R and Δr_{die} respectively equal to 0.25t-0.5t and 0.65t, the die geometry can be manipulated to obtain minimum strain heterogeneity besides a remarkable imposed plastic strain.

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