ON THE EFFECTS OF ECCENTRICITY IN PRECISION FORGING PROCESS

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Initial location of the billet and the shape of die have an important effect on parameters of precision forging. Some of these effects are the contact stresses, material flow, distribution of stress, and also strain. In the present study, the die shape influences and the billet position in precision forging of two different shape groups have numerically and experimentally been investigated. Results proved that a properly positioned billet leads to smooth material flow without defects of producing burrs and underfilling during the forging process. Problems such as die underfilling and wear are primary factors to restrict the growth of the precision forging in many occasions. Results show that small eccentricities between die and billet cause noticeable effects on required forging forces. This relationship strongly depends on the die shape. In order to evaluate numerical results, a series of experiments were designed and implemented on axi-symmetric parts in three different billet positions. It is observed that the results of the finite element method (FEM) investigations and the experiments are in well agreement

Keywords: Eccentricity, Billet position, Material flow, Precision forging.

1. Introduction

Precision forging is increasingly becoming popular in modern plastic working. Advantages like shortened production cycles which are achieved by eliminating post-machining operations and saving of raw material contribute to the growing cost-saving trend in mass production [1]. In this regard, many attempts have been done to increase productivity, to prolong die life, to improve die performance, to lower the costs, and to guarantee mechanical and metallurgical properties in the forged components. At the moment, the trend in mass production is toward eliminating post-machining.

Mechanical components are generally machined to meet specifications of final dimensions. However, flow lines become discontinuous by machining, which degrades mechanical properties such as fatigue strength and corrosion resistance [2].

Thus, precision forging is now developing fast to completely eliminate post-machining operations. Many parameters in the process of forging can affect the output. One of the most important issues which completely cannot be avoided is errors in positioning of the billet in its appropriate place in the die. In the most

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cases, the presence of such an error is inevitable due to work conditions and high temperature of the billet. In precision forging, since the process permits no material to escape, appropriate die shape and the billet position are crucial to forging process and its parameters. These parameters include the force needed to forge the billet, final stress and strain distribution, material flow pattern, and contact pressure stresses between the die and billet (die wear).

To attain better properties, some theoretical and experimental researches have been done in order to optimize relevant conditions in precision forging process. Sadeghi et al. [3] studied on parameters that affect the dimensional accuracy in axi-symmetric precision-forged components. They found out that forging force has a great effect on final dimensional accuracies. Siegert and co-workers [4] studied on controlling the parameters in precision forging by using a CAE software.

Mei Zhan et al. [5] studied on the influences of the initial position of preform on precision forging of a compressor blade. Using a 3D rigid-visco-plastic FEM, they found out that if a long and slender preform was bent in advance, a product without flash could be produced. Dong-Kyun Min and Min-Eung Kim [6] studied on the possible improvements for the steering yoke of automobiles by a rigid-plastic FEM. The corresponding results can be successfully applied in the case of mass production. Behrens et al. [7] did a general research into precision forging processes for high-duty automotive components and exemplarily devised an adopted method to manufacture a crankshaft.

Yanqiu Zhang et al. [8] investigated on controlling the flow lines in relatively complex shapes in isothermal precision forging. They showed that radial flow lines distribute along the forging shape, more easily than the axial flow lines do. Finally, they put forward some reasonable measures to optimize the flow lines.

In closed-die forging, Altan et al. [9] introduced relationships to calculate the stress and required force and also, calculate the parameters such as thickness and width of flash. The methods given by other researchers have also been reviewed in this paper. Using a finite element method, new factor of complexity was firstly defined by Mori and Li [10] based on the peak load, strain, and the die filling state. Slip line method has been introduced by Biswas and Ramesh [11] in the forging process.

Wang and Lin studied the forging by an upper bound approach which was a combination of stream function and FE method [12]. The effect of flash and burr sizes on the die filling were studied by Saniee and your co-worker, Hosseini [13]. The recent numerical investigations on the matter emphatically on different applications have well been reviewed by Hartley and Pillinger [14]. Hou and Stahlberg [15] developed a system for the automatic material flow analysis by IPT (Image Processing Techniques). Also, for a long shape closed-die forging, these researchers studied material flow, too [16]. An upper bound technique has been applied for designing the axi-symmetric forging by Lee and co-workers [17].

In the closed dies, simulation and correct prediction of flash formation were investigated in FEM by Tomov et al. [18]. Moreover, Ranatunga et al. [19] analyzed the forging forces, die filling factor, strain and strain rate in forging of axi-symmetric parts. In non axi-symmetric forging, Kwan [20] introduced a method based on an upper bound approximation. Saniee and Jaafari [21] analytically, numerically, and experimentally studied and compared the results of different closed-die forging procedures.

This paper attempts to determine the effects of die shape and billet position, two of influential parameters in the precision forging, on different factors like forging force, stress-strain distribution, material flow and contact pressures between the die and billet (die wear) by using 3D-FEM simulation, statistical methods, and a set of experimental examinations in two different shape groups with opposite flow directions.

Certainly, both quantitative and qualitative findings are helpful tools to minimize the problems such as underfilling, folding and severe die wear. For example, these results can be useful to decide whether a fixture for positioning the billet in correct point is necessary. Forging force as an important factor is seriously related to final cost. The higher forging force is required, the more expensive equipment is needed. Homogeneity in stress and strain distribution is necessary to uniformity of mechanical properties in material bulk. Furthermore, to have a homogenous ductility, deviation from the average grain disorder and strain hardening should be small enough to satisfy desired mechanical properties. Therefore, strain distribution and deviation from the average amount imply the product reliability.

The other parameter is material flow in die cavity which has influence on the final product properties. For instance, poor material flow cuts off metal flow lines, which can't satisfy the demands in many industries due to structure strength reduction. Bad material flow patterns lead to occurrence of the defects like underfilling or billet folding. In some cases, material flow imperfections result in uneven die wear and influence on friction stress and consequently on the die life. Considering geometrical features, this paper has categorized the shapes of the forged specimens.

For two categorized shapes, then, analytical formulations and FEM approach have been employed to determine the effects of billet location/position in the die. The analytical formulations will be used to calculate the required forging force, factor of material flow. Meanwhile, FEM approach has been used too. The experimental results are found in a well agreement with the FEM predictions.

2. Analyses

Available analytical investigations are based on several assumptions. The ideal work, the slab analysis, the upper bound, and the slip-line field methods are the most important ones. Based on these assumptions, undoubtedly, none of them is able to exactly calculate real condition parameters. Regardless of these simplifying assumptions, indeed, they are poor to evaluate some crucial factors like eccentricity, material flow, and non-homogenous deformations. For more clarity, the following paragraphs have briefly described the methods [22].

The ideal work solution: It is a lower bound plus the easiest theoretical method. It assumes the required work for deformation must be equal with the external work. Therefore, important relations of the method can be written as follow [22]:

$$W_i = \int_0^{\varepsilon} \sigma \, d\varepsilon \quad (1)$$

$$W_i = k\varepsilon^{n+1} / (n+1) \quad (2)$$

Where W_i is the ideal work, strain $\varepsilon = \ln(A_0 / A_f)$ in which A_0 and A_f are the initial and final cross sectional areas, respectively. The stress $\sigma = k\varepsilon^n$ in which k is the yield shear strength, and n is the work hardening factor. Some factors such as friction and non-homogeneity are neglected in this model [22].

The slab analysis method: Unlike the ideal work model, second one is the slab analysis method which consider friction coefficient. This model is able to determine the role of friction coefficient; although, friction does not influence the orientation of the principal axes, deformation is assumed to be homogenous. Moreover, the principal axes are in the directions of the applied forces. Considering Fig. 1, based on the slab analysis and by making a force balance on differential element, final relation of this method for the case given in this figure could be achieved as below [22]:

$$\mathrm{P}_{\mathrm{total}} = 2\mathrm{k} \exp\left(\frac{2\mu \mathrm{x}}{h}\right) \quad (3)$$

$\mathrm{P}_{\mathrm{total}}$ is the pressure applied to the specimen with constant coefficient of friction, μ.

The upper bound technique: It is based on satisfying yield criteria. This method focuses on the self-consistency of geometry. In this model, there is no work hardening, material is homogenous, and the deformation just is happened on a few planes and the other zones are rigid [22].

The slip-line field solution: This method is geometrically self-consistent as well as statically admissible. In this method, the material is rigid perfect plastic, isotropic, and homogeneous. Also, deformation is as plane-strain, temperature effects as well as strain rate are neglected, more to the point, the amount of shear stresses is assumed to be constant at interfaces [22].

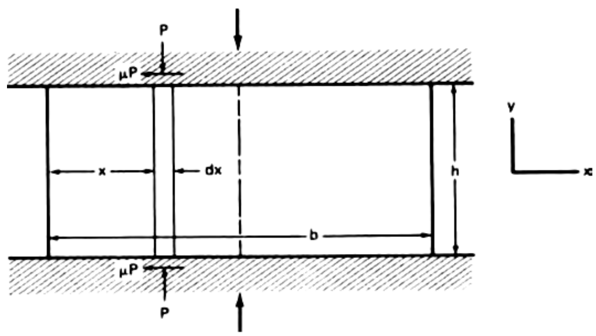

Fig. 1. Analysis of plane-strain compression process using the slab method [22]

Taking aforementioned discussion into account, none of the above solutions describes billet eccentricity effects and material flow. More importantly, unlike the above theoretical methods, the effects of geometrical specification have been studied in this paper. As it will be discussed in the next sections, it is represented that the billet eccentricity and material flow have significant effects on forging parameters.

2.1. Numerical analysis

According to the previous section, there is no analytical formulation being able to determine the effects of eccentricity on parameters of forging like the required forging force, die wearing, and so on. The above analytical approach doesn't tackle these problems. However, in most industrial applications, the billets are too hot and it is very hard to an operator to exactly locate the billet in die center. It's also clear that the operator hasn't enough time to centralize the billet in the center of die cavity because of mass production; in addition, productivity and time consuming are severely related to each other. This paper could provide and optimize an FEM model to achieve the best agreements between the test results and simulations. In the other words, simulation parameters like the element type, the element size, and so on have accordingly been chosen to provide an optimum model to predict relevant parameters in real conditions. Eccentricity effects could exactly be evaluated and determined. Finally, based on the developed model and that two shape groups having completely different material-flow plus the model can be extended to lots of other complex problems, ABAQUS/Explicit code (version 6.3) based on elastic-plastic finite element method has been used to predict the metal flow and other parameters in precision forging process. The 3D elastic-plastic FEM was introduced in simulations to yield more accurate results. Workpieces were used for both FEM and experimental tests (for disk shapes with unilateral hub being made of soft lead), input data was defined for mechanical properties associated with soft lead so that simulation results could be compared together. The accurate description of the contact conditions between the workpiece and tools is important to obtain numerical results which are equivalent to the real forming process. The shear friction factor 'μ' at the interface between the billet and die was assumed 0.2 (the most common friction coefficient for the steel dies).

Meshing was performed using C3D8R element (Eight-node brick element with reduced integration). The C3D8R element is a general purpose linear brick element, with one integration point. Due to the default hourglass control available in Abaqus C3D8R element could be used effectively in the present work. The reason is that the shift of stress from lateral elements is rather smooth and gradual. In addition, using triangular elements lead to severe distortions and jump in stress value in adjacent elements.

Through several iterative trials and errors, it became evident that for each analysis, there is an optimum value for element number leading to the desired results. Using less than this value would not deliver desired accuracy. On the flip side, using a number far more than that of optimum value would waste the time. The upper die moves only downward and deforms the billet into the cavity between upper and lower part of the die-set. In order to be able to study the effects of billet position, both in simulations and experiments, eccentricity of billet with the die was only changed. The velocity of upper part of the die is 60 mm/min for all simulations - similar to practical ones. In this way, it is possible to compare the results for different billets in spite of their various heights and die strokes.

3. Experimental test set-up

In industries, up to 30% of the forging parts are included in parts with axi-symmetric geometries. This paper categorizes these axi-symmetric parts into two groups i.e. additional elements on the middle and one side of the billet. Fig. 2 and table 1 illustrate an axi-symmetric geometry. To study the effects of billet position on the forging process, for the first group (i.e., disk shape with rim), three different cylindrical billets were considered. Both billet and die temperature is room temperature. Forging speed adopted for the experiments is semi static in order to eliminate strain rate' influences; meanwhile materials' flow stress is 38 MPa. Volume of final part and hence the volume of these three billets was 106028.8 mm³ based on volume incompressibility and the flash less nature of the process. For each configuration, three different eccentricity values were predicted and defined.

Table 1.

Three different configurations of billet for the part given in Fig. 2.

Configuration No.	Diameter (mm)	Length (mm)	Eccentricity value (mm)		
1	42	76.5	2	4	6
2	50	54	2	3	4
3	54	46.3	1	2	3

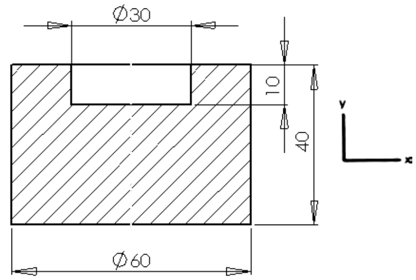

Fig. 2. Geometrical specifications of the parts in the first group

For the second group (i.e., disk shape with additional element on the middle of billet), three different cylindrical billets were considered. Since the four configurations used in experimental tests being made of soft lead, four different cylindrical billets were used as soft lead in simulation processes with attributed mechanical properties obtained from tension tests. With distinguishing feature of having a flashless process, the final volume of the part and the volume of these billets was 62046.45 mm^3. More to the point, lead is strain rate sensitive and recrystallization of such material could be happened even in room temperature; therefore, for taking strain rate effects into account, the strain-stress test was carried out to extract real stress-strain curve in order to be exerted in FEM ABAQUES simulations. It should be emphasized that since the speeds of stress-strain test and forging process both are the same (semi quasi static), a reliable comparison can be done between the results. For each configuration, three different eccentricity values were considered. These configurations are listed in Table 2. Also, the final forged part of this group is illustrated in Fig. 3.

Table 2.

Three different configurations and corresponding eccentricities of billet for the part in Fig. 3.

Configuration No.	Diameter (mm)	Length (mm)	Eccentricity value (mm)		
0	32	77.1	2	4	6
1	36	61	2	4	6
2	40	49.4	2	3	4
3	44	40.8	1	2	3

Using soft lead as the test material was more cost-effective due to using cheaper forge equipments. Besides, soft lead in room temperature has a reasonable formability. Mechanical properties of specimens were extracted from tension tests and then were fed to FEM software. Some of the mechanical properties are illustrated in Table 3.

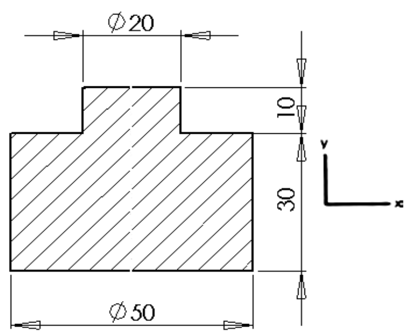

Fig. 3. Disk shape with middle elements on one side (final part)

Table 3.

Mechanical properties for the soft lead at room temperature

Tensile Properties		Poisson ratio
Yield strength, min (MPa)	Module of elasticity (GPa)	
33	17	0.45


Fig. 4. Specimens prepared for forging

After casting the workpieces in aluminum dies, by using a CNC lathe machine, all the workpieces were prepared in desired sizes and tolerance limits, afterwards. Finally, to prepare billets for tests, surfaces of workpieces were meshed by grid lines. Through using a CNC lathe machine and with a sharp-tip tool, these grid lines were engraved on surface of the workpieces. As shown in Fig. 4, these lines were used to measure the final strain in the workpieces.

The upper and lower parts of die were made of VCN150 and the other parts were built from wrought steel. As it was mentioned previously, the ram velocity for all of the workpieces was taken to be 60mm/min, and the lower die was fixed. Then, the practical tests were performed using an automatic hydraulic press in room temperature.

4. Results and discussions

This section presents evaluations between the simulation and experimental results. The number of shapes was so high that all sample preparations could be impossible. Therefore, three sets of eccentricities for four billet sizes have been performed only for the parts with an additional element in middle of the parts. For the second group (i.e., disk shape with unilateral hub), both experimental tests and FEM analysis were done and compared together.

Comparison of the FE results with experimental ones revealed that there is a good compatibility between them. According to similarities among the shapes and the other specifications of the parts, this validation can be generalized for the other parts or specimens.

Since the stress and strain distributions were similar, in this study, the strain distributions were only presented. For measuring the statistical homogeneity of strain distribution throughout the billet bulk - both in the tests and software - strain values for all the elements were imported in Microsoft EXCEL and then the averages and standard deviations were determined, too. For three configurations of first shape group (i.e., disk shape with middle elements on one side), Figs. 5, 6, and 7 show the strain distribution and material flow in both the middle and in the end of process.

Effects of billet position in disk shape with rim parts on strain deviation from the average, forging force, and average contact pressure relative to eccentricity amount are presented in Fig. 8.

For the first group, as in Fig.8a, a bit increasing in billet eccentricity leads to enhancement in stress (strain) averages and produces an optimum point for minimizing the deviation from them (Fig. 8a). Effect of such a point is more noticeable in smaller diameters. Also, increasing in billet eccentricity leads to increase in material flow (as it is shown in Fig. 8c), and consequently, to raise the forging force.

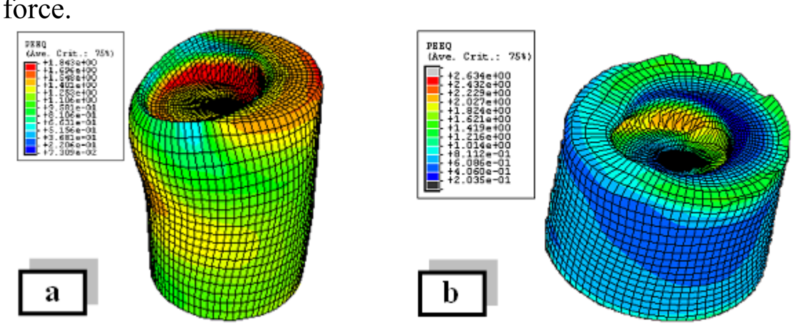

Fig. 5. Strain distribution pattern; (a): in the middle of process, (b): at the end (Billet diameter = 42 mm, Eccentricity = 6 mm)

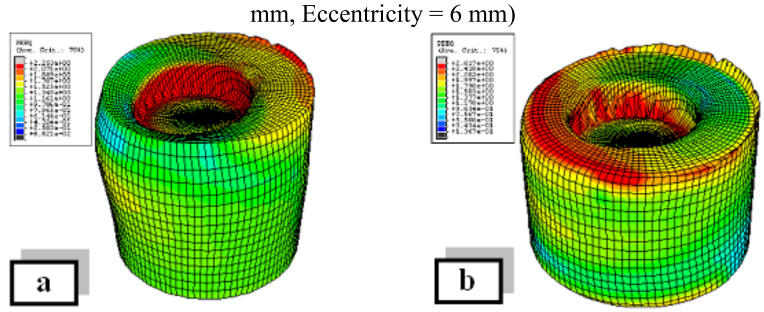

Fig. 6. Strain distribution pattern; (a): in the middle of process, (b): at the end (Billet diameter = 50 mm, Eccentricity = 4 mm)

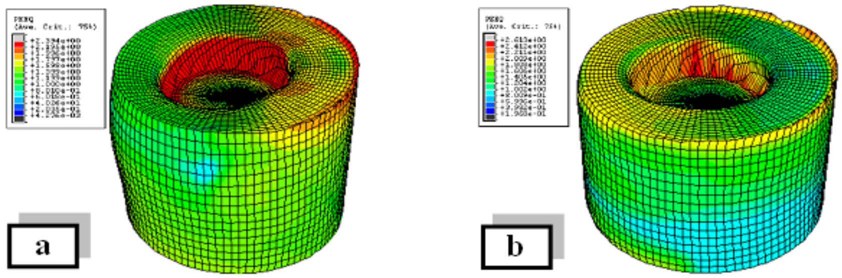

Fig. 7. Strain distribution pattern; (a): in the middle of process, (b): at the end (Billet diameter = 54 mm, Eccentricity = 3 mm)

In Fig. 8b, it is obvious that increasing in billet eccentricity in disk shape with rim leads to an increase in forging force, but this relation is not linear. The reason maybe is that, when the eccentricity increases, in order to fill the cavity, the amount of material flow increases, and apparently forging force must be raised. At the same time, when billet eccentricity increases, since shear forces raise (because of billet bending), forging force tends to decrease.

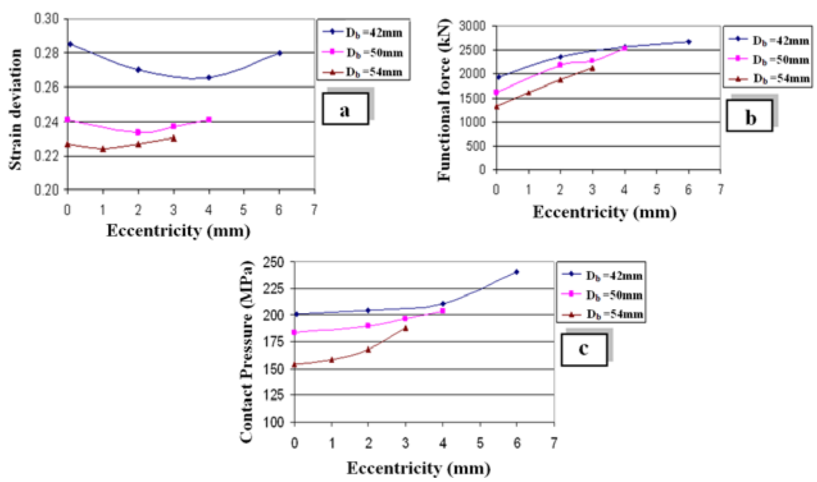

Fig. 8. (a): Strain deviation from average, (b): force, (c): Contact pressure

Similar to the first group, both in the middle and in the end of process, Figs. 9, 10 and 11 show the strain distribution and material flow for three configurations of the second group (disk shape with unilateral hub). For this group, increasing in billet eccentricity leads to increase in average strain and produces an optimum point to minimize average stress.

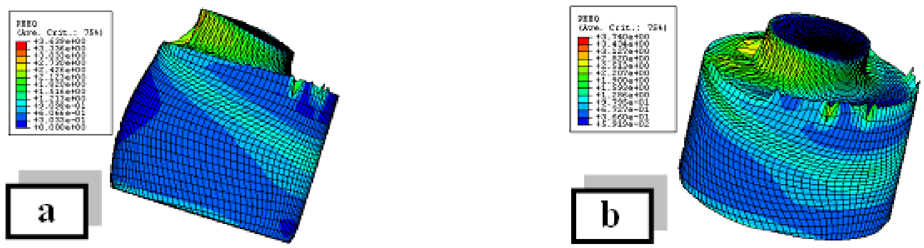

Fig. 9. Strain distribution pattern; (a): in the middle of process, (b): at the end of process (Billet diameter = 36 mm, Eccentricity = 6 mm)

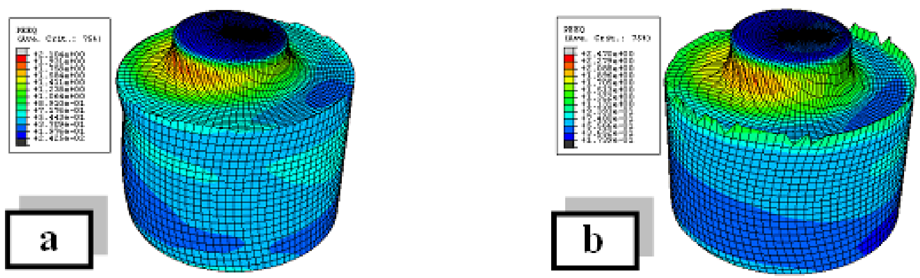

Fig. 10. Strain distribution pattern; (a): in the middle of process, (b): at the end of process (Billet diameter = 40 mm, Eccentricity = 4 mm)

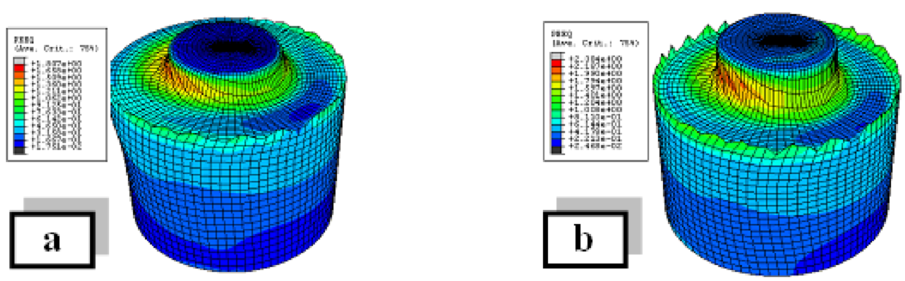

Fig. 11. Strain distribution pattern; (a): in the middle of process, (b): at the end of process (Billet diameter = 44 mm, Eccentricity = 3 mm)

Effects of eccentricity in disk shape with unilateral hub parts on strain deviation from the average, contact pressure and forging force are shown in Fig. 12. As it is obvious in Fig. 12a, there is an optimum point for standard deviation of the stress and strain. In order to have more homogeneous mechanical properties, it is recommended to put billet eccentrically to a reasonable degree. An optimal amount of eccentricity can be helpful to the forging force reduction. The higher amounts, the more severe strain gradients would be led in bulk of workpiece. In second group, as Fig. 12b shows, there is an optimum point to minimize the contact pressure and die wearing. There are two opposing factors: although in small eccentricities, because of rising in shear stresses, forging force and thus, contact pressure decreases, in big eccentricities, due to enhancement in material flow, strain hardening is intensified and therefore, contact pressure increases. In usual forging processes, as 15–20% of the total production cost is only needed for the die, an accurate control on forging parameters is the most important parameter to lengthen die life.

For this group, increasing in billet eccentricity leads to decrease in forging force. This is because of growing the shear stresses in bulk of billet material. Because of more material flow in higher eccentricities, the forging force will increase. This transition leads to produce an optimum point with the minimum forging force (as it is shown in Fig. 12c). By putting the billet at a reasonable distance from cavity center, a reduced deformation force and power demand effectively brings up an improvement in die service life. In occasions that press capacity has a restriction, reducing the forging force is inevitable.

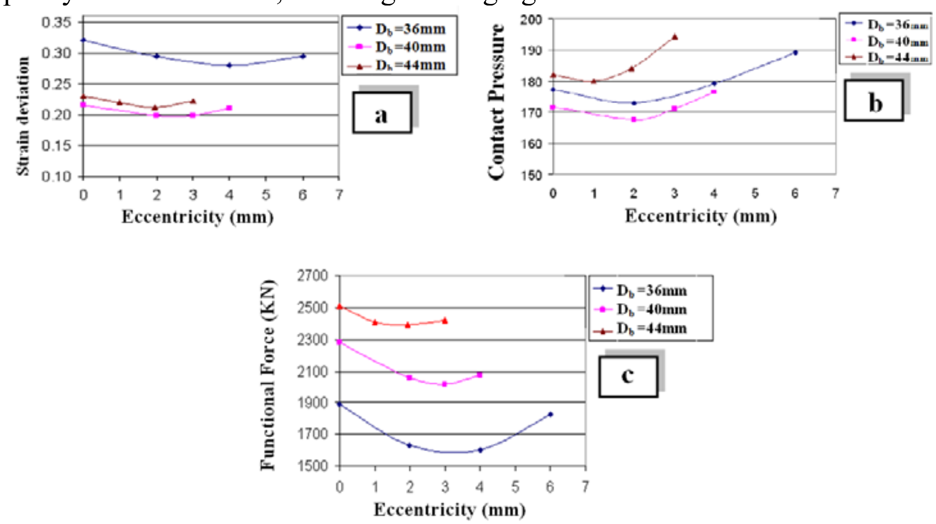

Fig. 12. (a): Strain deviation from average, (b): Contact pressure, (c): force

Figs. 13 and 14 show a complete graphical comparison between the experimental tests and simulations for four configurations of disk shape with unilateral hub parts in three different positions for each one. As Figs. 5a and 9a illustrate above, when eccentricity increases, material flow in one side being closer to the die wall decreases and in the other side, the amount of material flow significantly increases. This leads to buckle the billets with smaller diameters as it is obvious in Fig. 5a. The other point is the escape of material and thus producing a flash in the side which the billet is closer to die wall, as shown in Figs. 13e and 14c. This results in die wear, underfilling, or in some cases destroying the die.

The usual die wear is the gradual enlarging of the die impression due to erosion of the die material, generally occurring in areas subject to repeated high pressures during forging operations [12]. So far, the more eccentricity is, the more surface of die is subjected to wear. However, considering material flow pattern and its consequences, eccentricity - to a degree that practical conditions allow us - should be avoided in order to resolve defects mentioned above, and to achieve a proper material flow in die cavity.

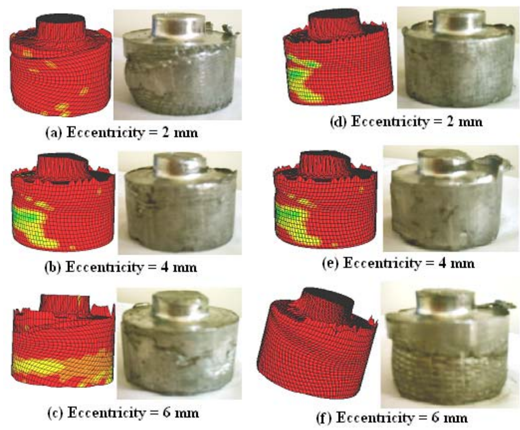

Fig. 13. Graphical comparison between practical tests and simulation results;
For a, b, c: billet diameter = 36 mm; For d, e, f: billet diameter = 32 mm

Fig. 15 shows the closeness between the experimental results and simulation answers for forging force and strain homogeneity. Fig. 16 exemplarily shows a comparison between theory and practice for 40 corresponding elements chosen from different points on specimen surface for the billet diameter of 36mm.

As it is obvious in Figs. 13, 14, and 15, the results obtained from simulations are in good agreement with those from experiments, and also, test results verified FE predictions with a higher accuracy. Some negligible differences between FEM and test results were probably rooted in factors like errors in grid lines engraving and dimensioning, anisotropic test materials, or stress concentration due to grid lines in the components. As compared with experiments, the 3D FEM makes it much quicker and cheaper to study the influences of the billet initial position on precision forging parameters with desirable accuracy. As both the experimental and FEM analysis have shown, billet position is crucial to forging parameters.

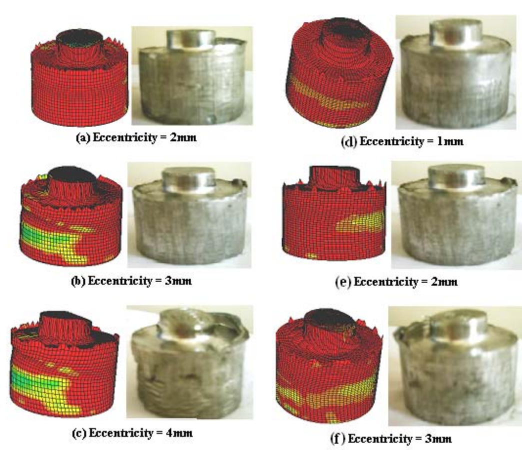

Fig. 14. Graphical comparison between practical tests and simulation results;
For a, b, c: billet diameter = 44 mm; For d, e, f: billet diameter = 40 mm

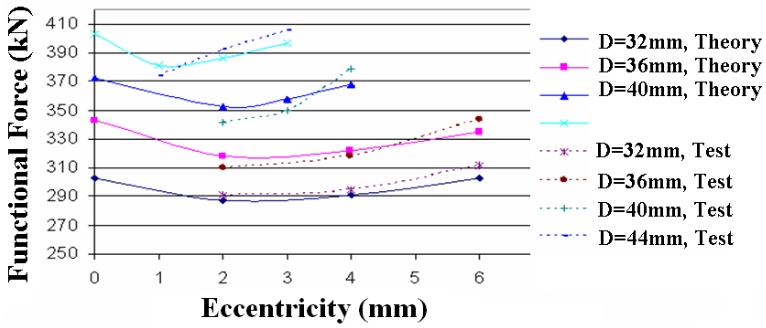

Fig. 15. Comparison of forging force values between the theory and experiment for disk shapes with hub

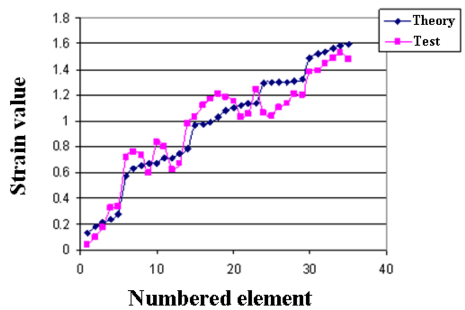

Fig. 16. Strain value for some corresponding elements and a comparison between the theory and experiment

5. Conclusions

In the present study, the effects of the different billet locations for the different billet size of two different shape groups have been studied though analytical, numerical, and experimental investigations.

It was revealed that the position of billet and forging die shape have a dominant effect on different parameters such as force and energy required, waste of materials, stress and strain characteristics, contact pressure, and successful die filling. Correct selection of the billet position in die cavity can lead to other advantages on the material flow, minimum defects, and also a low wear in components. As presented in the paper, selection of billet locations depends on specimen shape and geometry. Determination of an appropriate location can highly lead to lower force required, less wastes, and minimum defects created in products. The influence of billet initial position on closed die flashless forging of two shape groups have been researched by 3D FEM. The conclusions obtained are as follows:

1. The material flow toward the gap between die parts is not desirable at all. In order to minimize it, the billet must be close enough to center of the cavity.
2. Too much eccentricity causes an overflowing of the die. This results in an overloading on die-set which may destroy the die or at least severely shortens its service life.

3. In the case of considerable eccentricity amounts, one side is filled earlier than that of nearer to the other side. Thus, the material flow conditions are liable to produce the underfilling. In order to ensure that the die cavity is fully filled, eccentricity of billet should be controlled.
4. It seems FEM results in precision forging are capable of predicting the real tests with a high degree of accuracy. Therefore, in other cases, FEM results could be relied on provided that the appropriate input data is fed to the software.
5. As the FEM simulation has been validated by experiments, it may be used alone with confidence to generate data controlling precision forging parameters including similar processes. As the final point, these findings are suitable inputs for multi-criteria optimization techniques for long-term success.
6. Part shape is crucial to forging parameters like forging force, contact pressure, material flow pattern, and strain distribution.

Nomenclature

W_i	ideal work	W_i	ideal work
ε	strain	k	yield shear strength
σ	stress	n	factor of work hardening
A_0	initial cross sectional areas	P_{total}	pressure applied to the specimen
A_f	final cross sectional areas	μ	friction coefficient

R E F E R E N C E S

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