

The Cold Forming Analysis of Eccentric Parts

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ABSTRACT

In this study, a multi-stage cold forming process for the manufacture of eccentric parts is studied numerically with low carbon steel AISI 1022. The forming processes through five stages and four stages include two-step forward extrusion, eccentric upsetting, and backward extrusion over a moving punch. The numerical simulations of cold forming are conducted using the code of DEFORM-3D. The formability of the workpiece is studied numerically, such as the effect on forging load responses, maximum forging loads, effective stress and effective strain distributions and metal flow pattern. The maximum effective stress of 819 MPa at the third stage is the largest among the stages. The maximum effective stresses of the last stages for the four-stage forming and five-stage forming are almost the same. The effective strain distributions of the last stages for the four-stage forming and five-stage forming are very similar. The flow line distributions of the last stages both for the four-stage forming and five-stage forming are also very similar. For the maximum axial forging force and forming energy, the third stage of eccentric upsetting at the upper end is the largest among the stages. The total maximum axial forging loads from the first to the last stages are 795.8kN for the five-stage forming and 590.4kN for the four-stage forming; and the total forming energies are about 0.751kJ for the five-stage forming and 0.671kJ for the four-stage forming. Although the total maximum axial forging loads and total forming energy of the four-stage forming are smaller than those of the five-stage forming, the maximum lateral forging force in the last stage of the four-stage forming is almost five times that of the last stage of the five-stage forming. Increasing lateral forging force may lead to wear and damage of the punch. Moreover, the inner surfaces of the hexagonal cavity at the upper end are relatively uneven because of simultaneous eccentric upsetting and backward extrusion in the last stage of the four-stage forming.

Keywords: cold forming, eccentric parts, formability, forging load, lateral forging force.

1. INTRODUCTION

Cold forging is performed at room temperature and is proverbially used in many industries, especially in the manufacture of fasteners and special parts. Good tolerances, high mechanical properties and good surface appearance are generally achieved without further machining. Since the successful development of multi-stage forging machines, multi-stage cold forging has been widely used to produce axisymmetric parts [1]. Multi-stage cold forging is a high-speed forming process in which billets are formed sequentially through multiple stations [2]. The cold forming process is widely used in the manufacture of various component products such as screws, bolts, nuts, rivets and special parts. In cold forging, the dies are subjected to higher stresses. Predicting forming loads and stresses is important for die design and machine selection.

There are many researches and analysis on cold forming processes. Many cold forming applications use numerical simulation to predict the forming design and the simulation parameter settings. Altan and Knoerr [3] applied the 2D finite element method to investigate suck-in type extrusion defects, bevel gear forging, stress analysis of forging tools and multi-stage cold forging designs. Oh et al. [4] discussed the features required to simulate cold forging operations and provided example solutions to demonstrate the performance of the DEFORM system. Joun et al. [5] proposed a numerical simulation technique for the forging process with a spring-attached die. A penalty rigid-viscoplastic finite element method was applied together with an iterative force-balancing method. They investigated significance of metal flow lines for quality control and the effects of spring-attached dies on the metal flow lines and the decrease in forming load. A three-stage cold forging process to form the spline shape in the head of an aerospace fastener was proposed by MacCormack and Monaghan [6]. They gained insight into the operation by numerically analyzing the strain, damage, and flow patterns for all three stages. Wu and Hsu [7] analyzed the effect of die shapes with different draft angles and fillet radii on extrusion forging deformation using finite element method. Two sets of dies with different shapes were performed and the results were compared with the predictions of the finite element method for the same deformation mode. Cho et al. [8] conducted a numerical study on the process design of cold forging operations for forward and reverse extruded axisymmetric parts. The results of numerical simulation are in good agreement with the experimental results. In order to analyze the formability of the multi-stage forging process, Park et al. [9] applied the finite element method to establish a systematic process analysis method for the multi-stage forming of a constant velocity joint outer race. Farhoumand and Ebrahimi [10] applied the FE code ABAQUS to the analysis of the forward-backward-radial extrusion process to investigate the influence of geometric parameters such as die corner radius and gap height and process conditions such as friction on the process. The numerical results are compared with experimental data in terms of forming loads and material flow in different regions. The hardness distribution of the longitudinal section of the product was used to verify the strain distribution obtained from the numerical analysis. Ji et al. [11] applied the numerical code of DEFORM_2D to study the forming mechanism of a five-stage cold extrusion process for shaft parts used in gearboxes. They showed that the five-stage cold extrusion process is feasible and obtained the forming rules. Jafarzadeh et al. [12] applied the FE code of DEFORM-3D to study the transverse extrusion process to analyze the effects of some important geometric parameters such as initial billet dimensions, gap height and friction conditions on the required forging load, material flow pattern and effective plastic strain distribution. They showed that the gap

height had the greatest influence on the forming load and material flow. This study analyzed and compared 4 and 5 stages of fasteners. They used the FE code of DEFORM-3D to inspect the effective stresses, strains and velocities of objects from billet material to finished material. Yang and Lin [13] performed numerical and experimental studies on two forming modes for two-step extrusion forming of AISI 1010 carbon steel. The numerical results for the effective strain distributions are consistent with the hardness distribution measured in the experiment.

Kang and Ku [14] used spheroidized SCr420H billets to conduct a series of experimental study on multi-stage cold forging for the outer race of a constant velocity joint with six inner ball grooves. The results showed that with the proposed multi-stage cold forging process, the outer race was well forged, and the dimensional accuracy of the forged outer race also met the requirements. A new metal forming process was proposed by Winiarski and Gontarz [15] to produce two-step outer flanges on hollow parts extruded by a movable sleeve. A two-stage cold forging process was proposed by Ku [16] to manufacture AISI 1035 steel drive shafts with internal spline and spur gear geometry. Al-Shammari et al. [17] designed a six-stage cold forming process using a 3D geometric model to manufacture AISI 1010 steel shells of spark plug. They applied numerical analysis to explore product part dimensions, forging loads, effective stresses, contact pressures, and velocity fields. The actual product part dimensions and forging loads of the six stages were compared with the FE simulation results to verify that the analysis results were acceptable. Byun et al. [18] studied numerically on multi-stage cold forging of SUS304 ball studs. They investigated the plastic deformation behavior of SUS304 from room temperature to 400°C and used a general method to express the flow stress as a close-form function of strain, strain rate, and temperature. It is optimal at high strains, especially during multi-stage cold forging. Winiarski et al. [19] performed a numerical study on a six-stage cold forging process of 42CrMo4 steel hollow flanged parts using DEFORM 2D/3D to determine whether the proposed forging technique could be used to produce flanged hollow parts. A multi-stage cold forging process using finite element analysis was developed by Jo et al. [20] to manufacture a high-strength one-body input shaft with a long body and no separate parts. They provided a proof-of-concept for the design and development of a multi-stage cold forging process to manufacture a one-body input shaft with improved mechanical properties and material recovery. Dubiel et al. [21] investigated the cold forging process of flanged bolts to obtain consistent, acceptable and inconsistent grain flow patterns, and correlated the FEM simulation results with the conducted experiments. Yang and Liu [22] performed a numerical and experimental study on a five-stage cold forming process for manufacturing relief valve regulating nuts with low carbon steel AISI 1010. The numerical simulation and experimental results were in good agreement for the forming force growth tendency. The effective strain distributions were consistent with the measured hardness distributions. Highly compacted grain flow lines also led to higher hardness.

This study presents the analysis of multi-stage cold forming process for the manufacture of eccentric parts. The forming process includes two-step forward extrusion, eccentric upsetting, and backward extrusion over a moving punch. The numerical simulation of cold forming is studied using the FE code of DEFORM-3D. The forming load responses are calculated and the metal flow pattern, effective stress and effective strain at various deformation zones are analyzed.

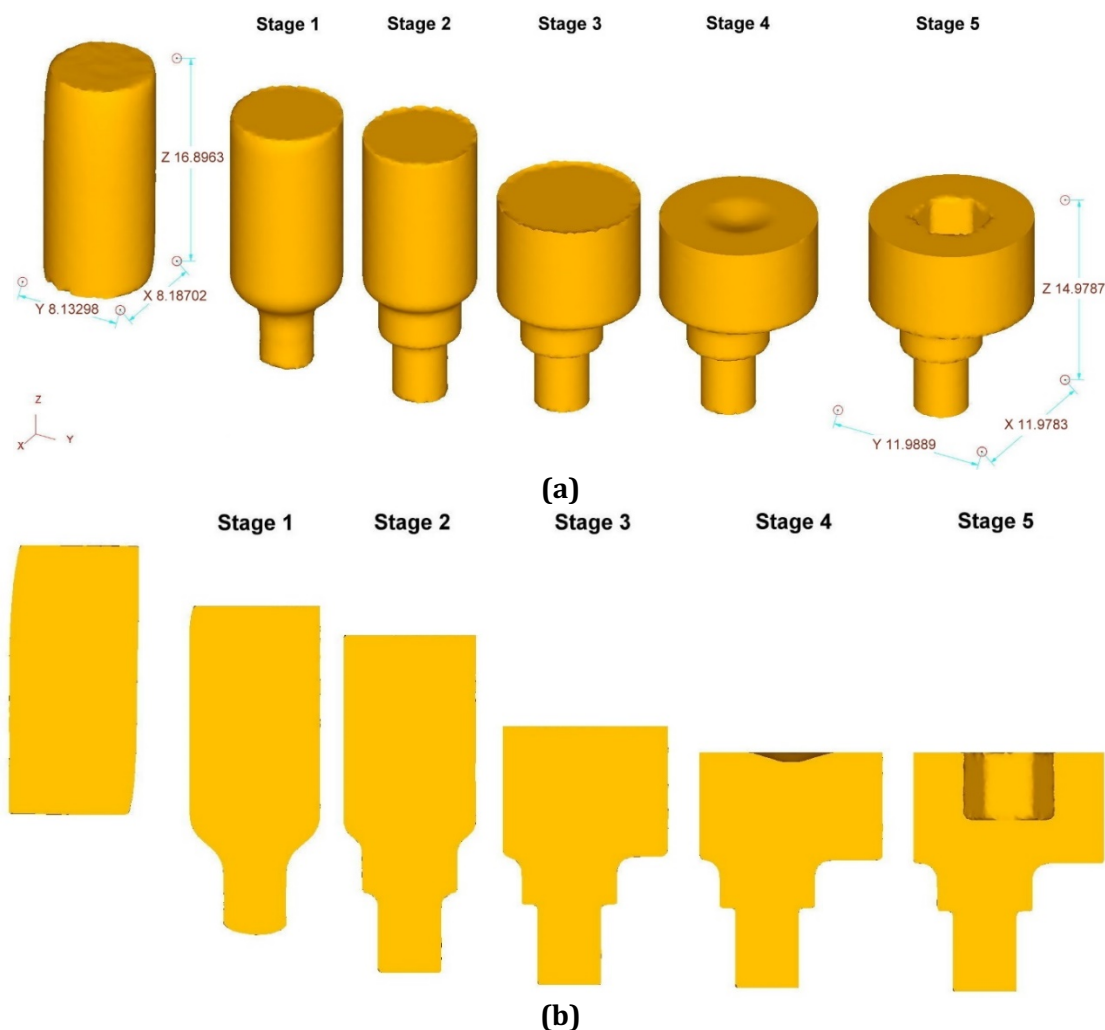
2. MATERIALS AND METHODS

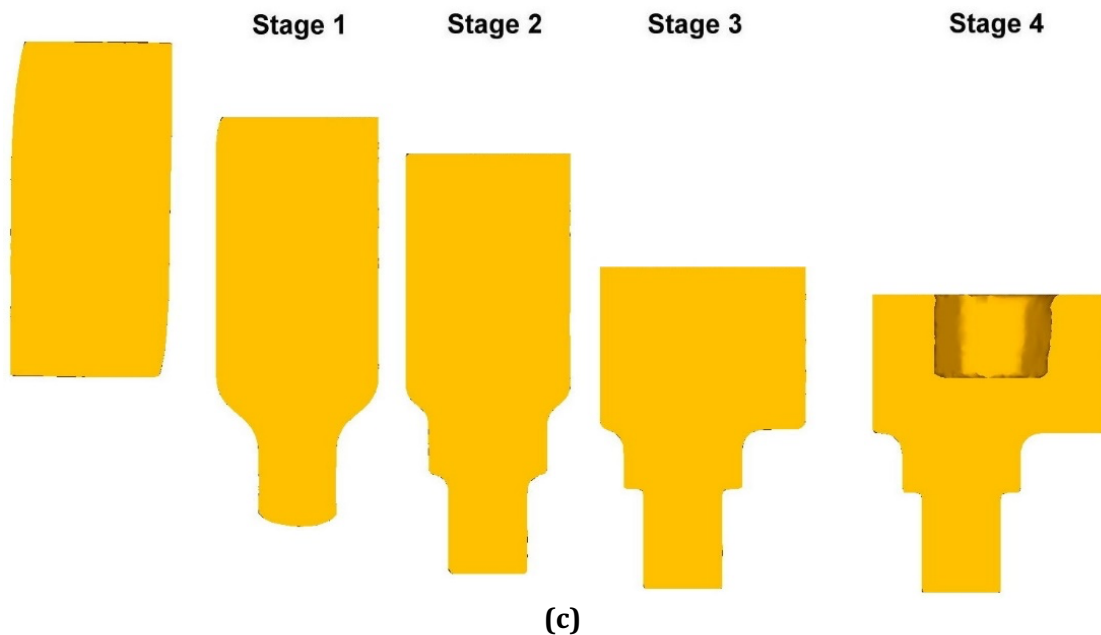
The manufacturing process of the eccentric parts is multi-stage cold forming through five stages or through four stages. A cold-forging quality AISI 1022 carbon steel wire coil used for the compression tests, which is manufactured by China Steel Corporation, Kaohsiung, Taiwan. The chemical composition of the carbon steel wire is shown in Table 1.

Table 1. Chemical composition of AISI 1022 carbon steel wires (wt.%).

C	Mn	P	S	Si	Cu	Ni	Cr	Al
0.22	0.77	0.013	0.007	0.04	0.06	0.01	0.04	0.034

The numerical study of cold forming is conducted using the FE code of DEFORM-3D. A billet of $\phi 8.1\text{mm} \times L16.8\text{mm}$ is cut by shearing die and transfer to forging stations. The 3D and cross-section views for initial billet and product parts of each stage are shown in Figure 1.





(c)

Figure 1. The shapes for initial billet and product parts of each stage. (a) 3D views for five-stage forming, (b) cross-section views for five-stage forming, (c) cross-section views for four-stage forming.

There is visible deformation to the ends of the cutoff billet, as shown in Figure 1, due to cutting to length by shearing. Therefore, the initial billet is no longer an axisymmetric cylindrical body. For the five-stage forming, as shown in Figures 1(a) and 1(b), the billet is firstly forward extruded with the reduction in area of 76.8% in the first stage, then, it is moved to the second stage in which the second forward extrusion process with the reduction in area of 47.7% is executed over a moving punch. Then the workpiece is moved to the third stage where the upper end of the workpiece is eccentrically upset by 1mm, and moved to the fourth stage where the workpiece is further eccentrically upset to 1.5mm and centering for backward extrusion. At the final stage, the workpiece is backward extruded over a moving punch to form a hexagonal cavity at the upper face. For the four-stage forming shown in Figure 1(c), at the final stage (fourth stage), the workpiece is further eccentrically upset to 1.5mm and simultaneously backward extruded over a moving punch to form a hexagonal cavity at the upper face. The deformation energy is

$$E = \int_0^{\Delta L} F dl \quad (1)$$

where F is forging load and ΔL is total acted forging stroke.

Numerical simulation of multi-stage cold forming is modeled as a 3D finite element analysis using DEFORM 3D. The workpiece is modeled using tetrahedral elements. Since the material of tools is usually much harder than the material of workpiece, their deformations are ignored and treated as rigid objects. The workpiece material is a AISI 1022 carbon steel billet which is considered as a rigid-plastic material with Von Mises yield criterion, isotropic hardening. For more accurate simulation results, a cylindrical compression test, with the specimens of $\phi 12.45\text{mm} \times L15.9\text{mm}$, are performed with a 20-tonne universal testing machine under a

constant ram speed of 3 mm/min at room temperature, and the following equations are used to obtain the true stress and true strain [23],

$$\sigma = P/A_0, \quad (2)$$

$$\varepsilon = (h - h_0)/h_0, \quad (3)$$

$$\sigma_t = \sigma (1 + \varepsilon) = \sigma (h/h_0), \quad (4)$$

$$\varepsilon_t = \ln(1 + \varepsilon) = \ln(h/h_0), \quad (5)$$

where σ is engineering stress, ε is engineering strain, P is compression force, A_0 is initial cross-sectional area, h_0 is initial height, h is the instantaneous height, σ_t is true stress and ε_t is true strain. Figure 2 demonstrates the true stress-true strain diagram of AISI 1022, which is required in simulation.

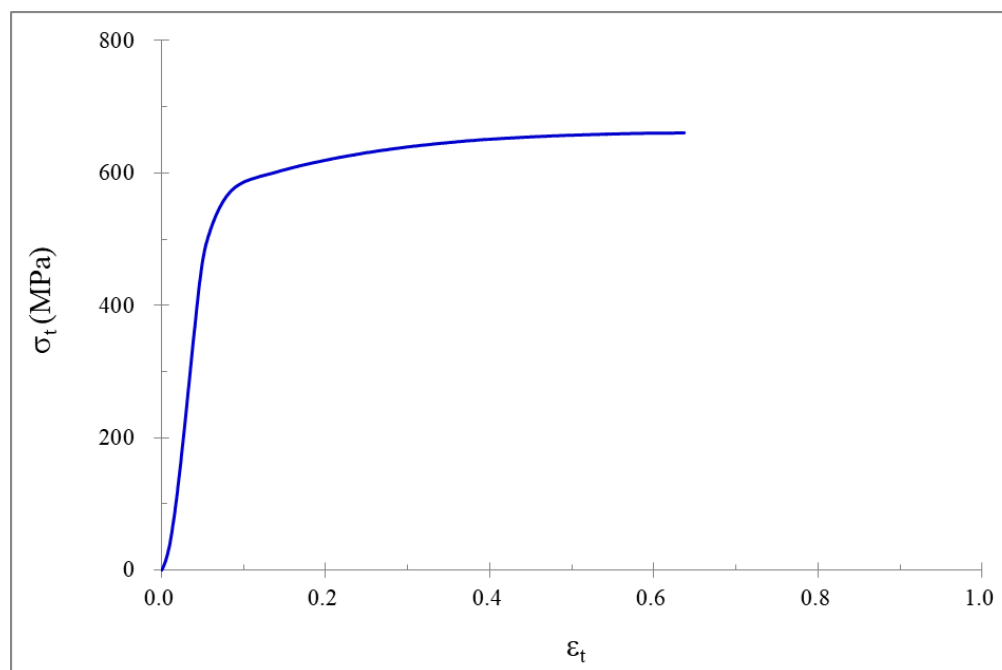


Figure 2. True stress-true strain curve of AISI 1022 by compression test at room temperature.

The friction between the workpiece and tools is considered as constant shear friction, and the friction coefficient is $m = 0.12$. The relevant simulation settings are shown in Table 2.

Table 2. Simulation parameters in DEFORM.

Workpiece material	AISI 1022
Workpiece/die property	Plastic/rigid
Temperature	20°C
Mesh number	35,000
Mesh element type	Tetrahedron
Friction model/friction coefficient	Constant shear friction/0.12

3. ECCENTRIC COLD FORMING

For the multi-stage cold forming of eccentric parts through five stages or four stages, the effect of forging load response, maximum forging load, effective stress and effective strain distributions, and metal flow pattern are studied numerically.

3.1 The Forging Load Response and Deformation Energy

The five-stage forming and the four-stage forming simulation results are respectively shown in Figures 3 and 4 for the axial loads (F_z) and the lateral loads (F_x). The maximum forging loads are indicated for each stage. The axial forging stroke (ΔL) and deformation energy (E) for each stage are listed in Table 3. For the forming loads, as shown in Figures 3 and 4, the axial loads are obviously much larger than the lateral loads for each stage.

From the force responses of forming load during all stages, the first three stages are the same both for the five-stage and the four-stage forming, as shown in Figures 3 and 4. It is observed that at first stage the maximum axial forging loads is 84.8kN, which is the first forward extrusion with the reduction in area of 76.8%, and the forming energy is 136.8J shown in Table 3. While, the maximum lateral forging force of 2.1kN is relatively small. In the second stage there is an increasing in maximum axial forging load at 150.8kN for the second forward extrusion with the reduction in area of 47.7%, while the forming energy of 81.0J is smaller than that of the first stage. And the maximum lateral forging force of 1.8kN is also relatively small. In the third stage, the maximum axial forging load is increased to 273.1kN for 1mm eccentric upsetting at the upper end of the workpiece, and the forming energy of 237.2J is also much larger than those of the first and second stages, as shown in Table 3. However, due to eccentric upsetting, the maximum lateral forging force of 3.7kN is larger than those of the first and second stages which are axisymmetric forming.

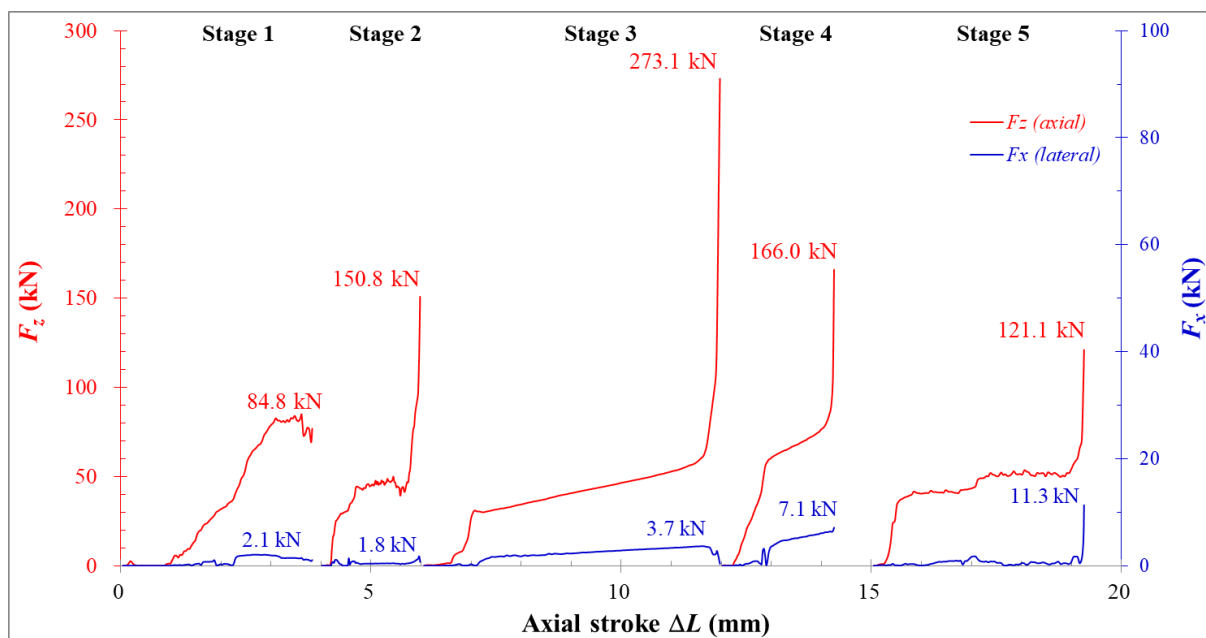


Figure 3. Forging loads versus axial stroke for five-stage forming.

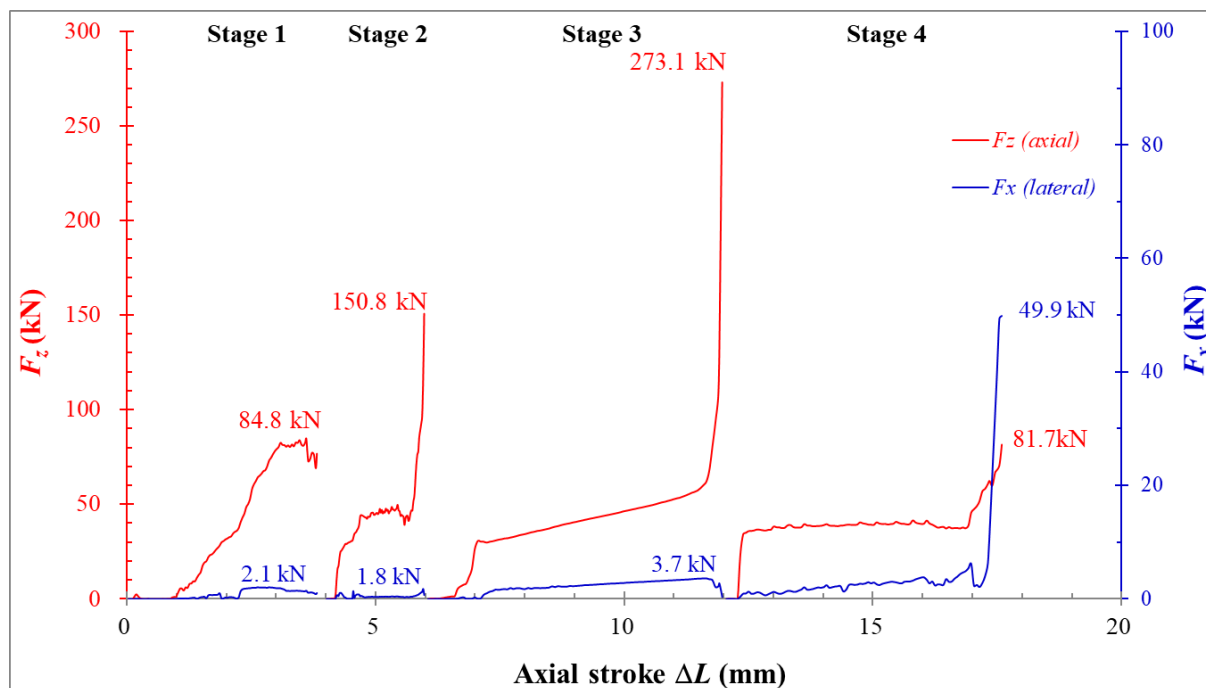


Figure 4. Forging loads versus axial stroke for four-stage forming.

For the five-stage forming, in the fourth stage, the workpiece is further eccentrically upset to 1.5mm and centering for backward extrusion. The maximum axial forging load of 166.0kN is smaller than that of the third stage, as shown in Figure 3, and the forming energy of 112.9J is also much smaller than that of the third stage, as shown in Table 3. However, the maximum lateral forging force of 7.1kN is larger than that of the third stage due to the further eccentrically upsetting. At the last stage (the fifth stage), a backward extrusion process is performed by a moving the punch to form a hexagonal cavity at the upper end, which includes a complex cavity shape, and requires high pressure to force the material fill the die cavity. The maximum axial forging load is increasing at 121.1kN which is smaller than those of the third and fourth stages. While, the forming energy of 182.9J is larger than that of the fourth stage but smaller than that of the third stage, as shown in Table 3. The maximum lateral forging force of 11.3kN is the largest of the five stages due to the eccentric forming.

For the four-stage forming, in the fourth stage (the last stage), the workpiece is further eccentric upset to 1.5mm and simultaneously backward extruded over a moving punch to form a hexagonal cavity at the upper face, which includes a complex cavity shape, and requires high pressure to force the material filling the die cavity. The maximum axial forging load of 81.7kN, as shown in Figure 4, is smaller than that of the last stage in the five-stage forming, but the forming energy of 216.3J, as shown in Table 3 is larger than that of the last stage in the five-stage forming. However, the maximum lateral forging force of 49.9kN, as shown in Figure 4, is almost five times of that of the last stage in the five-stage forming due to the large amount of eccentric forming.

For the maximum axial forging force, as shown in Figures 3 and 4, the third stage, which the upper end of the workpiece is eccentrically upset by 1mm (Figure 1), is the largest among the multi-stages, For the forming energy, as shown in Table 3, the third stage is also the largest

among the multi-stages. Overall, the total maximum axial forging loads from the first to the last stages are 795.8kN for the five-stage forming (Figure 3) and 590.4kN for the four-stage forming (Figure 3); and the total forming energies shown in Table 3 are about 0.751kJ for the five-stage forming and 0.671kJ for the four-stage forming. Although the total maximum axial forging loads and total forming energy of the four-stage forming are smaller than those of the five-stage forming, the maximum lateral forging force in the last stage of the four-stage forming is almost five times that of the last stage of the five-stage forming. Increasing lateral forging force may lead to wear and damage of the punch. Moreover, the inner surfaces of the hexagonal cavity at the upper end are obviously uneven, as shown in Figure 1(c), because of simultaneous eccentric upsetting and backward extrusion.

Table 3. The acted axial forging stroke (ΔL) and deformation energy (E) for each stage.

	Stage	1	2	3	4	5	Total
Five-stage forming	E (J)	136.8	81.0	237.2	112.9	182.9	750.9
	ΔL (mm)	3.82	1.98	5.97	2.25	4.25	
Four-stage forming	E (J)	136.8	81.0	237.2	216.3		671.4
	ΔL (mm)	3.82	1.98	5.97	5.59		

3.2 The Effective Stress Analysis

The effective stress distributions are shown in Figure 5 at the final position of each stage for the five-stage forming and four-stage forming, and the maximum effective stresses are indicated. For the first stage, stresses are arising at the upper end and the forward extrusion region of workpiece when they are in contact with the dies, then the stresses increase as the forging load increases, the maximum effective stress is 751 MPa. It is observed that the highest value of effective stress occurs in the upper end and the forward extrusion region whereas the lowest value of effective stress occurs in the lower end and the middle region of workpiece. For the second stage which involves the second forward extrusion over a punch, it is analyzed from Figure 5 that the effective stresses are high in the upper end and the extrusion deformation region. Lead a two-step rod at lower end is formed which needs to high pressure in turn cause high effective stress of 755 MPa on workpiece and tool surface. Since the initial billet is not an axisymmetric cylindrical body, the effective stress distributions in the first two stages are obviously not axisymmetric, as shown in Figure 5, even though they are axisymmetric forming. In the third stage, the upper end of the workpiece is eccentrically upset by 1mm. As the punch stroke increasing, eccentrically upsetting formation begins. The stress response is significantly larger for almost the entire workpiece, as shown in Figure 5. The maximum effective stress is 819 MPa.

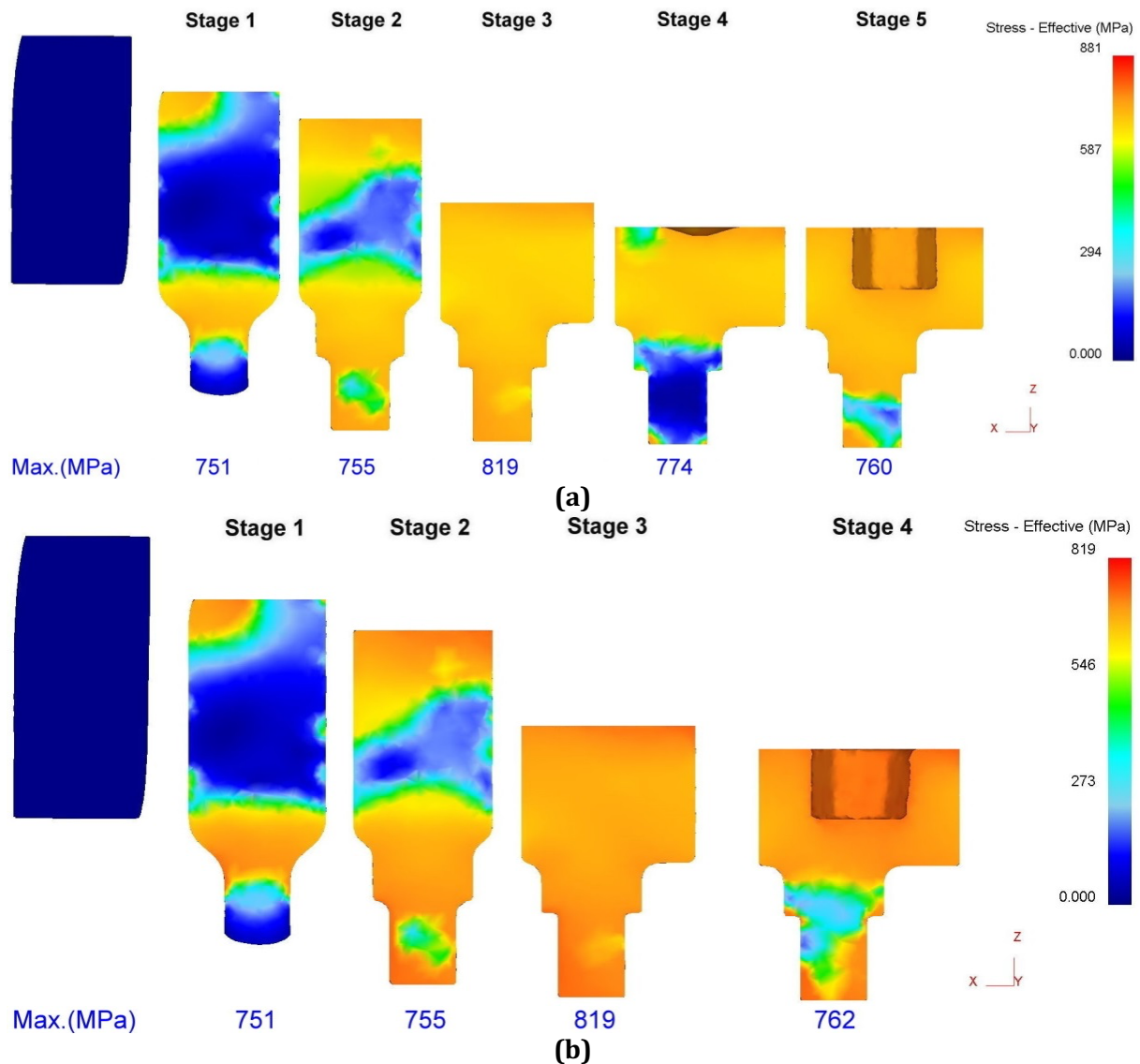


Figure 5. The effective stress distributions at the final position (a) for five-stage forming and (b) for four-stage forming.

For the five-stage forming, in the fourth stage, the process of eccentric upsetting over a moving punch is carried on to form a 1.5mm eccentric head and centering for backward extrusion. This results in the formation of the eccentric head in the upper face under high pressure, resulting in high effective stress of 774 MPa. The stress response is evidently large in overall upsetting region of workpiece, as shown in Figure 5(a). At the fifth stage (the last stage), a backward extrusion process is performed by a moving the punch to form a hexagonal cavity at the upper end. This leads to the formation of a hexagonal cavity in the upper face under high pressure, leading to a high effective stress of 760 MPa. The stress response in overall backward extrusion region of workpiece is obviously larger, as shown in Figure 5(a).

For the four-stage forming, in the fourth stage (the last stage), the workpiece is further eccentrically upset to 1.5mm and simultaneously backward extruded over a moving punch to form a hexagonal cavity at the upper face. This leads to the formation of an eccentric head and a hexagonal cavity at the upper end under high pressure, leading to a high effective stress

of 762 MPa, as shown in Figure 5(b). The stress response in overall the upsetting and backward extrusion regions of workpiece is evidently larger. Although the maximum effective stresses of the last stages for the four-stage forming and five-stage forming are almost the same, the inner surfaces of the hexagonal cavity at the upper end are evidently uneven for the four-stage forming, as shown in Figure 5(b), because of simultaneous eccentric upsetting and backward extrusion.

3.3 The Effective Strain Analysis

Figure 6 shows the effective strain distributions at the final position of each stage for the five-stage forming and four-stage forming. In the first stage, the effective strains in the upper end and the forward extrusion regions of workpiece are higher than the middle region where the deformation is small, as shown in Figure 6. For the second stage of the second forward extrusion over a punch, the effective strains are high in the upper end and the region of forward extrusion forming with large deformation. However, even if the first two stages are axisymmetric forming, their effective strain distributions are also obviously not axisymmetric, as shown in Figure 6, because the initial billet is not an axisymmetric cylindrical body. For the third stage of 1mm eccentric upsetting the upper end of the workpiece, the effective strains are obviously high in the upsetting zone and the lower end compression over a die pin, while the effective strains of the other region are relatively small, as shown in Figure 6.

For the five-stage forming, in the fourth stage, the process of eccentric upsetting over a moving punch is conducted to form a 1.5mm eccentric head and to center for backward extrusion. the effective strains are higher in the upsetting end and the lower end compression over a die pin, while the effective strains of the other region are relatively small, as shown in Figure 6(a). At the fifth stage (the last stage), a backward extrusion process is conducted by a moving the punch to form a hexagonal cavity at the upper end. The effective strains are evidently high in the overall region of backward extrusion with large deformation, as shown in Figure 6(a), as well the lower end compression over a die pin.

For the four-stage forming, in the fourth stage (the last stage), the workpiece is further eccentrically upset to 1.5mm and simultaneously backward extruded over a moving punch to form a hexagonal cavity at the upper face. The effective strain response in overall the upsetting and backward extrusion regions of workpiece is evidently larger, as shown in Figure 6(b), which is similar to that of the last stage for the five-stage forming. However, the inner surfaces of the hexagonal cavity at the upper end are evidently uneven for the four-stage forming, as shown in Figure 6(b).

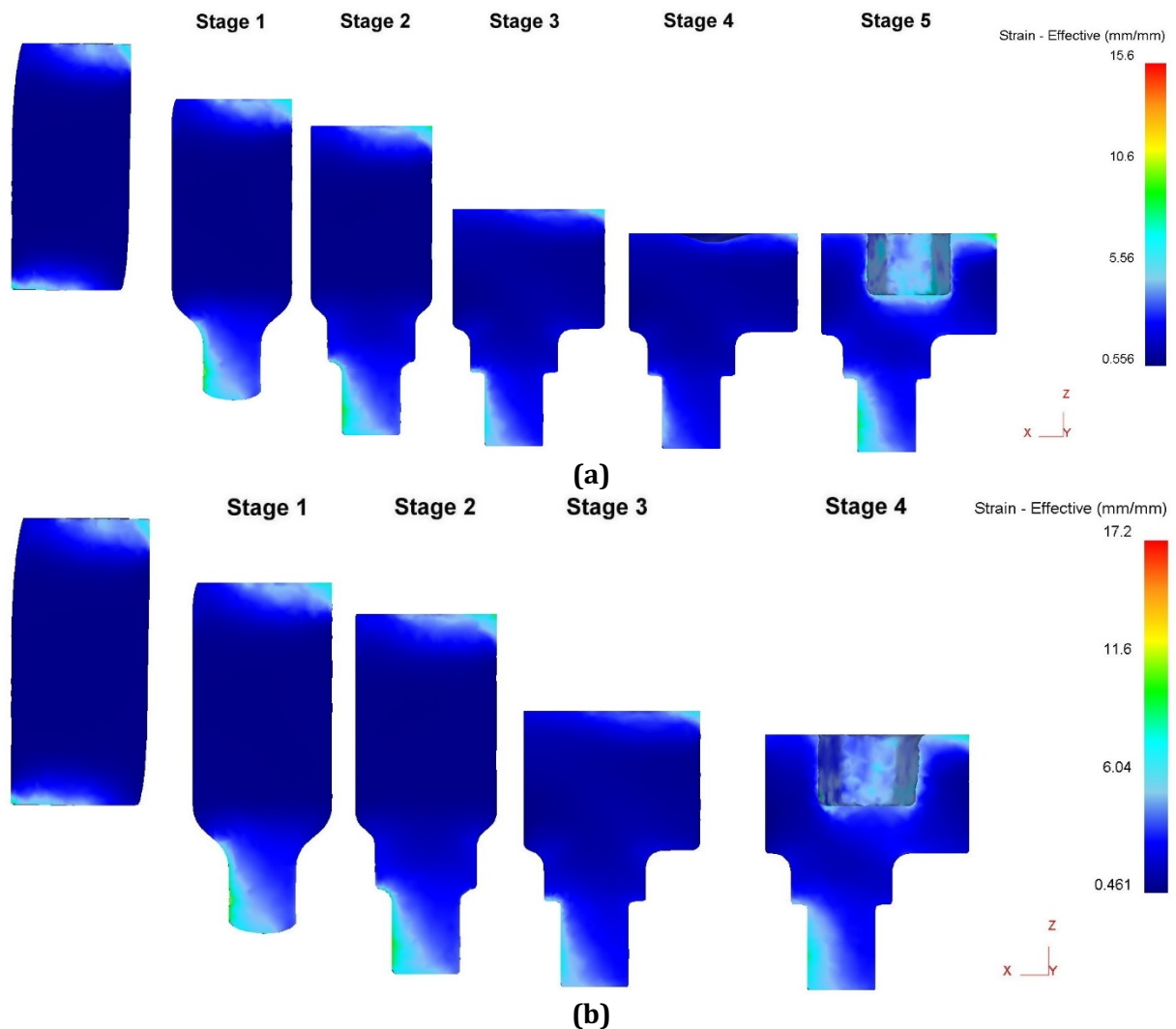


Figure 6. The effective strain distributions at the final position (a) for five-stage forming, (b) for four-stage forming.

3.4 The Flow Line Analysis

When the metal is deformed by cold forging, the deformed grains and inclusions are distributed in bands along the main elongation direction of the metal forming the grain flow lines. Figure 7 shows the simulation results of flow lines for the five-stage forming and four-stage forming. The flow lines in the initial billet are almost evenly distributed, as shown in Figure 7, except at both ends where the flow lines are vertically bent and highly compacted because of shear deformation. Highly compacted flow lines lead to higher hardness [22].

In the first stage, the flow lines in the upper end and the forward extrusion region of workpiece are highly compacted, while in the middle region with low deformation, the flow lines are almost evenly distributed, as shown in Figure 7. For the second stage of the second forward extrusion over a punch, the flow lines in the forward extrusion regions are obviously highly compacted. In the third stage, the flow lines in the lower region of eccentric upsetting head are curved and highly compacted, as shown in Figure 7.

For the five-stage forming, in the fourth stage, the flow lines in the lower region of eccentric upsetting head are heavily curved and highly compacted due to further eccentric upsetting, as shown in Figure 7(a). For the fifth stage (the last stage) of backward extrusion over moving punch to form a hexagonal cavity, the flow lines are more severely curved and highly compacted in the zone beneath the hexagonal cavity because of backward extrusion forming, as shown in Figure 7(a).

For the four-stage forming, in the fourth stage (the last stage) of further eccentric upsetting and simultaneous backward extrusion with a moving punch to form a hexagonal cavity at the upper face, the flow lines are more severely curved and highly compacted in the zone beneath the hexagonal cavity because of severe structure deformation, as shown in Figure 7(b), which are very similar to those of the last stage for the five-stage forming.

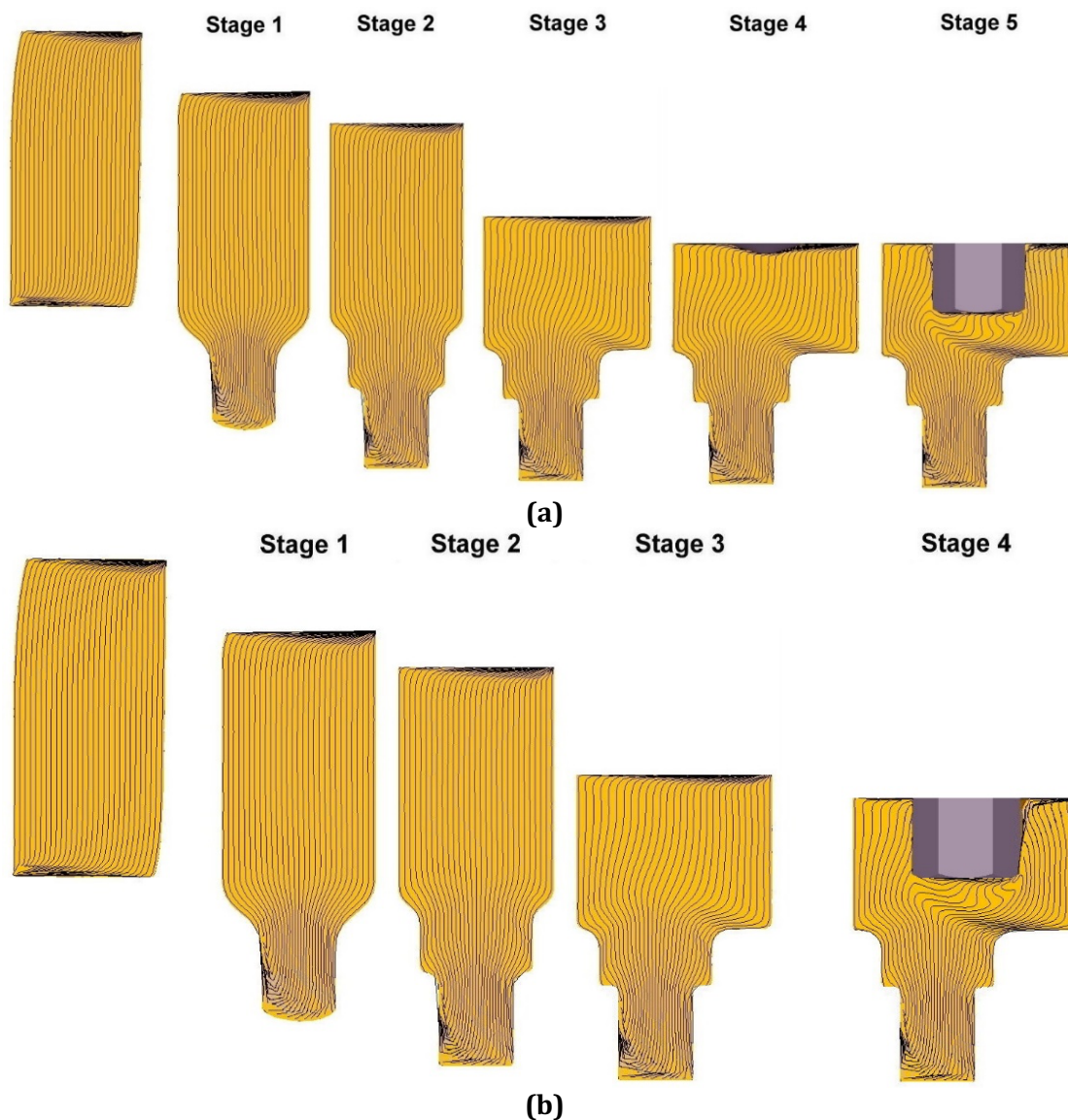


Figure 7. The simulation results of flow lines at the final position (a) for five-stage forming, (b) for four-stage forming.

4. CONCLUSIONS

In this study, a multi-stage cold forming process for the manufacture of eccentric parts is studied numerically with low carbon steel AISI 1022. The forming processes through five stages and four stages include two-step forward extrusion, eccentric upsetting, and backward extrusion over a moving punch. The numerical simulations of cold forming are carried out using the FE code of DEFORM-3D. The formability of the workpiece is studied, such as the effect on forging load response, maximum forging load, effective stress and effective strain distributions and metal flow pattern.

The maximum effective stress of 819 MPa at the third stage is the largest both for the five-stage and four-stage forming. The maximum effective stresses of the last stages for the four-stage forming and five-stage forming are almost the same. The effective strain responses of the last stages for the four-stage forming and five-stage forming are very similar. The flow line distributions of the last stages both for the four-stage forming and five-stage forming are also very similar, which are more severely curved and highly compacted in the zone beneath the hexagonal cavity because of severe structure deformation.

For the maximum axial forging force and forming energy, the third stage of eccentric upsetting at the upper end is the largest among the multi-stages. The total maximum axial forging loads from the first to the last stages are 795.8kN for the five-stage forming and 590.4kN for the four-stage forming; and the total forming energies are about 0.751kJ for the five-stage forming and 0.671kJ for the four-stage forming. Although the total maximum axial forging loads and total forming energy of the four-stage forming are smaller than those of the five-stage forming, the maximum lateral forging force in the last stage of the four-stage forming is almost five times that of the last stage of the five-stage forming. Increasing lateral forging force may lead to wear and damage of the punch. Moreover, the inner surfaces of the hexagonal cavity at the upper end are obviously uneven because of simultaneous eccentric upsetting and backward extrusion in the last stage of the four-stage forming.

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