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ORIGINAL RESEARCH

A new criterion for preform design of H-shaped hot die forging based on shape complexity factor

Reza Hosseini-Ara [1] · **Pouya Yavari** [2]

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Abstract In this paper, a new criterion is proposed in order to determine the necessity of preform steps for axisymmetric H-shaped parts in multi-stage hot forging based on shape complexity factor. The proposed geometrical based criterion was implemented in several examples using finite element method and experimental tests to verify the presented criterion. Finally, in comparison with the existing criteria, results show that the proposed criterion is in excellent agreement with experimental results in order to estimate the optimum number of preform steps.

Keywords Hot forging · Preform design · Shape complexity factor · Finite element method · Experimental test

Introduction

Forging is currently one of the most economical processes for manufacturing the engineering parts. In this process, material flows and plastic deformation causes the work piece to fill the dies. In fact, one of the main objectives of forging process design is to provide complete and flawless die filling so that the desired finished part geometry can be obtained without any internal or external defects. However, in some cases the shape complexity of the final part causes some defects to form in the part. Some examples of these defects are: inadequate die filling, non uniform flow of material, die surface wear, increasing the forces applied on dies and folding defects in forged parts. Thus, it is not possible to perform the process in only one stage and preform stages are necessary [1]. Therefore, forging in multiple steps can improve the process and material properties such as reducing the press loads, wearing of the dies, and flash materials while it makes more uniform deformation, etc. [2]. In fact, preform dies are used when the final shape of the product is complicated and it causes to ensure the appropriate control of material flow in order to fill the die cavity and acceptable surface finish [3].

Hence, the preform design in multi-stage forging plays a key role in improving product quality, such as ensuring defect-free property and proper flow of materials. In industry, preforms are generally designed by the iterative trial-and-error approach. However, this approach leads not only to the increase of significant tool cost but also to the extended down-time of the production equipment [2]. For this end, some numerical methods have been developed for simulation and analysis of different metal forming processes. In fact, numerical methods using high-speed computers have brought opportunities for process design. Park et al. introduced backward tracing method for preform design of shell nosing [4]. Also, Badrinarayanan and Zabaras developed a sensitivity analysis method for preform design of an axisymmetric disk upsetting case in order to minimizing the barreling effect [5].

In fact, determination of the number of preform steps is very important in multi-stage forging; however, researchers have not found an exact answer for this question. Several methods and criteria have been established for estimating the required number of preform steps. One common approach for determining the preform of H-shaped cross sections is the Brukhanov and Rebelsky criterion [6]. They divided H-sections into two groups based on the ratio of the height of the wall to its width, and proposed a preform for each group.

✉ Reza Hosseini-Ara
HosseiniAra@pnu.ac.ir

[1] Department of Mechanical Engineering, Payame Noor University, Tehran 19395-3697, Iran

[2] Department of Mechanical Engineering, Jasb branch, Islamic Azad University, Jasb, Iran

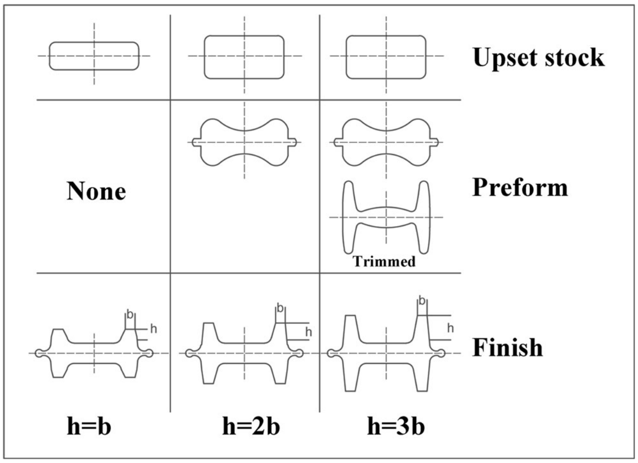


Fig. 1 The number and shapes of preform dies for H-shaped parts as proposed by Thomas [8]

Chamouard offered another method for determining the preform of sections with high walls and narrow passages which also comprises H-sections [7]. Thomas also divided the preform of H-sections into three groups based on the ratio of the height of the wall to its width [8]. However, a review of the previous works reveals that no comprehensive approach has yet been presented to determine the preform steps for parts with various section shapes.

To this end, shape complexity factor (SCF) is one of the most applicable methods for determining the preform steps. In fact, shape complexity of the final part affects the flow of materials and like the other parameters has its own measure that depends on the definition of SCF. Recently, Tomov has presented a new SCF for axisymmetric forging parts by calculating the work done for plastic deformation [9–11].

Therefore, the present study proposes a comprehensive and novel approach for designing preform dies using SCF in axisymmetric hot die H-shaped forging. New criterion based on geometrical properties of cross section and distribution of materials in dies was applied to determine the number of preform stages. Also, the new criterion was examined on several examples using finite element method (FEM). Moreover, in order to verify the validity of the FEM results, a similarity study between FE analysis and different experimental tests was made. Finally, comparison of the new approach with the existing ones for different H-shaped parts shows that the presented criterion is more accurate in estimating the number of preform steps.

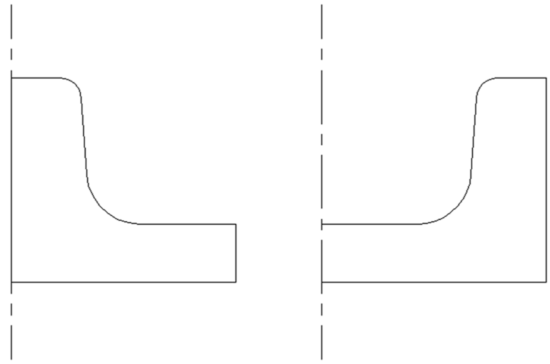


Fig. 3 Example of two different sections with same "*DAR*" and "*AAR*" ratios

Shape complexity factor

The flow of material into the deep recesses and concave corners of the finishing die cavity will provide the largest increase in the SCF [12]. This factor is also defined for other metal forming processes. For example, the complexity of an extrusion, according to a popular definition [13], is a function of the ratio of the perimeter to the cross-sectional area of the part, known as the complexity index or shape factor.

In the literature, Kinzle and Spies presented a first definition of SCF for metal forging, based on the mass of the forging parts [14]. However, the first applicable SCF is defined by Teterin et al. for axisymmetric parts as follows [15]:

$$S_T = \frac{P_F{}^2/A_F}{P_C{}^2/A_C} \times \frac{2R_{gF}}{R_C} \tag{1}$$

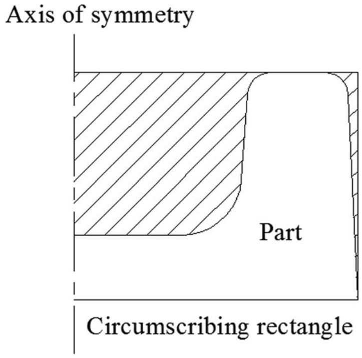


Fig. 2 "Dead Area" and "Active Area" for an axisymmetric H-shaped part

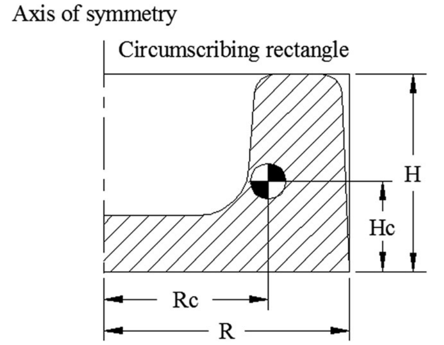


Fig. 4 Determination of "*RDR*" and "*ADR*" ratios

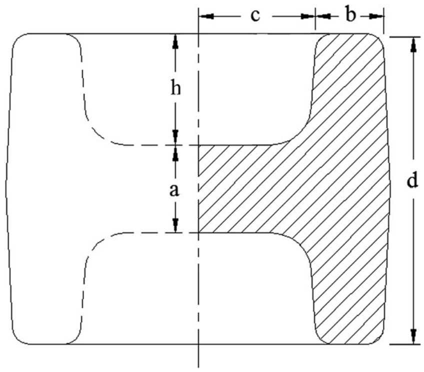


Fig. 5 Shape and parametric dimensions of axisymmetric H-shaped part

where P_F and A_F are the perimeter and surface area of the axial cross section, P_C and A_C are the perimeter and area of a circumscribing cylinder, R_{gF} is the distance of the center of gravity from the axis of symmetry and R_C is the radius of the circumscribing cylinder. For a multistage process, the SCF of the final stage was proposed by Zhao et al. [12] as below

$$S_F = \frac{S_{FF}}{S_{FP}} \tag{2}$$

where S_{FP} and S_{FF} are the SCF for preform shape and final forged part. It is obvious that if the final shape is a cylinder, then the SCF for this part is one and for more complex shapes, the factor will be larger so that the necessity of preform stages will be larger for a defect free forging.

Moreover, Thomas technique is used to obtain the shape and number of preform dies for H-shaped sections based on the complexity of final forging parts [8]. Thomas divided H-sections into three groups according to the ratio of the height of the wall to its width as presented in Fig. 1.

Finally, Tomov presented a new SCF for axisymmetric forging parts by calculating the work done for plastic deformation [9]. Tomov believed that the presence or lack of the preform steps would depend on the following condition:

$$W^* = (1-K_1)\varphi_A + K_1 > \varphi_H \tag{3}$$

where K_1 describes the amount of the transformed volume during two arbitrary stages of forging, φ_H is the logarithmic height strain and φ_A is the logarithmic strain on the cross sectional area of the part. On the basis of Tomov's criterion, if condition (3) holds for a part, then preform stage is necessary.

New preform design criterion

Basically in forging, there are some different SCF definitions and corresponding criteria for preform design of forging parts but these criteria cannot estimate the necessity of perform stages accurately in the field of hot closed die forging. In fact, this weakness is because of the lack of an exact investigation of all effective parameters in determining the SCF of a forging part. In the present study, some other important geometrical parameters that can influence SCF are investigated. By the means of these parameters, new criterion is defined. For this purpose, it is necessary to determine the concept of SCF and its effective parameters.

In fact, shape complexity is one of the most important factors that can influence material flow. On the basis of some research and geometrical rules, cylinder is the least complex shape among the 3-D parts [12]. In fact, cylinder is an axisymmetric part with a cross section of rectangle in 2-D analysis. So, the amount of deviation of the cross section from its circumscribing rectangle is one of the most important parameters to determine the SCF. Maybe that is why Teterin offered his criterion. Therefore, an appropriate scale for measuring this kind of deviation is "Dead Area Ratio" and "Active Area Ratio" [16]. As illustrated in Fig. 2, the ratio of the section area of a part to the area of its circumscribing rectangle is named "Active Area Ratio" or "*AAR*" in brief. In the similar way, the ratio of the dead area (hatched) to the circumscribing rectangle area is named "Dead Area Ratio" or "*DAR*".

In this research it is proved that the SCF of a certain cross section will be larger when "*DAR*" is increased. On the other hand, the scale of these two ratios is varied for different types of sections, so these ratios are not enough to determine the complexity of a part. For example in Fig. 3, "*DAR*" and "*AAR*" values of both sections are the same but their complexities are not.

Table 1 Results of Teterin, Thomas and Tomov criteria in comparison with the new criterion

Case	Part geometry				Teterin		Thomas		Tomov			New criterion	
	a	b	c	d	S_T	Preform step	$\frac{h}{b}$	Preform step	W^*	φ_H	Preform step	SCF	Preform step
c1	90	60	100	210	1.77	No	1	No	0.84	0.90	No	0.66	No
c2	45	60	100	165	2.24	Yes	1	No	0.89	0.92	No	0.91	No
c3	45	60	100	245	2.61	Yes	1.6	No	0.92	0.97	No	1.10	Yes

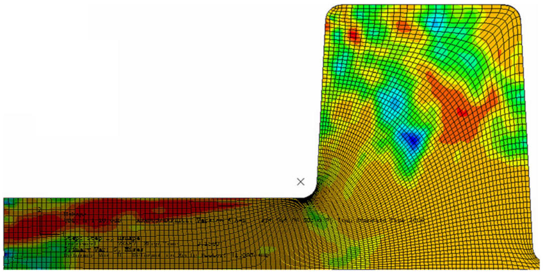


Fig. 6 FEM simulation for case c2

Therefore, in this case there must be another parameter that can affect SCF of one part, and this could be the distribution of dead area and active area on the circumscribing rectangle. For this end, two factors are defined to measure this kind of distribution. These factors are named "Axial Distribution Ratio" (*ADR*) and "Radial Distribution Ratio" (*RDR*). These two factors are defined as the ratio of the height (*Hc*) and radius (*Rc*) of the cross section's centroid to the height (*H*) and radius (*R*) of circumscribing rectangle, respectively as illustrated in Fig. 4.

In fact, the increase in these ratios means that material has to flow a longer distance and that means the shape complexity is greater. These ratios are determined as below

$$RDR = \frac{R_c}{R} \quad (4)$$

$$ADR = \frac{H_c}{H} \quad (5)$$

After determining the effective parameters, new SCF based on these factors is shown as

$$SCF = \frac{2 \times RDR \times ADR}{AAR} \quad (6)$$

where, "*AAR*" is the active area ratio, "*RDR*" and "*ADR*" are the material distribution ratios and the constant two is used for equalizing the effect of distribution ratios in the equation similar to that in Teterin's criterion. Finally, based on the new SCF, new criterion for preform design of axisymmetric H-shaped part is given as

$$SCF > 1 \quad (7)$$

In fact, this new criterion is based on these influential factors and also geometrical dimensions of the section and it is not related to the material properties because of the similar behavior of most metals and alloys at high temperatures used in hot forging.

Finally, if condition (7) holds, then at least one preform step will be necessary. In this case, it is required to calculate Eq. (6) for preform design and then if condition (7) holds, another preform step will be necessary. Also, another application for condition (7) is for optimizing the shape of preform dies. In fact, if one preform design does not match in condition (7), the number of preform stages will be decreased.

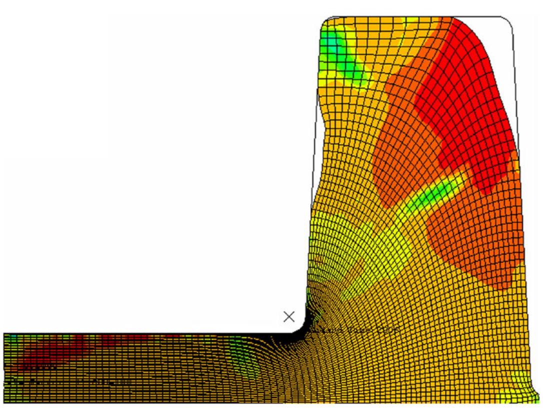


Fig. 7 FEM simulation for case c3

Fig. 8 Configuration of dies assembly for closed hot die forging of case c3

Fig. 9 The experimental forged sample of case c3

Fig. 10 Final forged sample of case c3 with plasticine modeling

Results and discussion

Numerical results

Herein, an axisymmetric H-shaped part with parametric cross section geometry is chosen as shown in Fig. 5 in order to have different SCF.

The results of different criteria are shown and compared with the presented criterion in Table 1.

As seen in Table 1, according to Teterin's criterion, results show that preforming steps are necessary for cases c2 and c3. Also Thomas' and Tomov's criteria show that preforming steps are not necessary for these cases. On the other hand, results of the new criterion show that preforming step is necessary for the case c3. In order to compare these different criteria, first we try finite element method (FEM). ABAQUS package for FEM simulation of metal forming processes have been used. In the FEM simulation, the initial work piece is Low-carbon steel with the diameter of 320 (mm) and the height of 260 (mm) and also the material of the die is H13. The initial temperature of billet and dies are 1100 °C and 400 °C, respectively. The results of FEM simulation are shown in Figs. 6 and 7.

As illustrated in Figs. 6 and 7, case c2 does not require preform step and the initial billet can directly deform in final dies, but for case c3 the dies were unfilled and the necessity of preform step is unavoidable. So, according to the FEM simulations, only the case c3 requires a preform step which is in contradiction with Thomas' and Tomov's predictions and it proves the new criterion.

Experimental results

Hot closed die forging

Beside the numerical results, some experimental tests were conducted. Here, case c3 from Table 1 is investigated for the experimental hot die forging study in order to verify FEM simulation results. In fact, unfilled dies in the experimental test for the case c3 show that Thomas' and Tomov's criteria cannot determine the necessity of preform step exactly in comparison with the new criterion. Here, the new criterion is in the form of non-dimensional, so the size of initial billet for the presented experimental test has the diameter of 32 (mm) and height of 26 (mm). Low-carbon steel with forging temperature $T_P = 1100$ °C has been chosen as deformed material for the experiment. Finally, the Configuration of dies assembly for closed hot die forging of case c3 and the experimental forged sample of case c3 are shown in Figs. 8 and 9 as below:

As seen in Figs. 8 and 9, the dies were unfilled and the preform step is necessary for case c3. Thus, according to the experiment, the case c3 requires a preform step which can verify the results of presented new criterion.

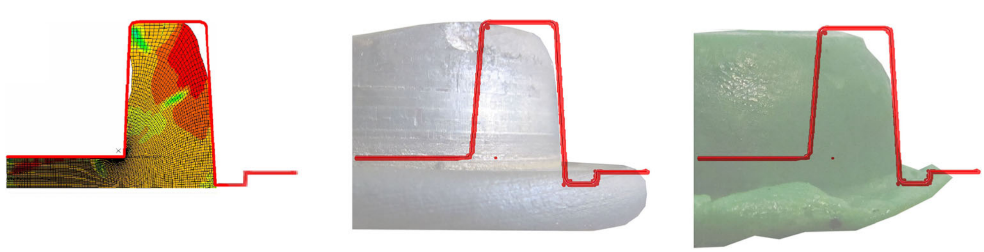
Plasticine modeling

Plasticine is one of the most widely used modeling materials for studying of plastic deformation of hot metal forming [17–19], because the experimental test with plasticine is inexpensive, very simple and easy to handle in a laboratory and so here it is investigated for verification of the results. The main content of plasticine is fine lime powder with grease as a binder. Its characteristic is very similar to deformation of hot steel. Herein, the final forged sample of case c3 with plasticine modeling is investigated as shown in Fig. 10.

Again, the dies were unfilled and the preform step is necessary for case c3. Hence, according to the experimental plasticine modeling, the case c3 requires a preform step which can verify the results of presented new criterion.

As shown in Fig. 11, an excellent agreement between the FEM simulation, experimental tests and the proposed criterion is found in order to estimate the optimum number of preform steps.

Fig. 11 Comparison of different results for the case c3 (**a**) FEM simulation (**b**) Experimental hot closed die forging (**c**) Plasticine modeling



(a) **(b)** **(c)**

Conclusions

Attempt has been made to come up with a new and more coherent definition of shape complexity factor (SCF) for hot die forging and a new criterion has been presented for the design of perform shapes for axisymmetric multi-stage hot die H-shaped forging. The presented criterion was tested on several examples using FEM simulations and experimental tests to verify the models. Comparison of the numerical and experimental results verifies the presented criterion and shows that the new criterion for axisymmetric H-shaped parts based on new SCF is more accurate in estimating the number of preform steps in comparison with the other existing criteria. The presented approach can be easily generalized to more complex geometries and is independent of the material model. In addition, another application for condition (7) is for optimizing the shape of preform dies. In fact, if one preform design does not match in condition (7), the number of preform stages will be decreased.

Moreover, there is a good correlation between FEM simulation, experimental test, plasticine modeling and new criterion using condition (7). Also, it is shown that modeling with plasticine can be another applicable method for studying the hot die forging and verifying the numerical results because it is inexpensive, very simple, and easy to handle in a laboratory.

Compliance with ethical standards

Conflict of interest None.

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