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Virtual Orthogonal Optimization in Upsetting of Cone End Billet with Large Height-To-Diameter Ratio

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To restrain bulging in the upsetting of the larger height-diameter ratio (LHDR) billet, a novel upsetting method named cone end billet upsetting (CEBU) is proposed in this article. This method is featured by prefabricating cone shape at billet ends, and aimed to obtain a smaller rigid deformation zone in forming. The forming characters of a cylinder LHDR billet were analyzed by the commercial finite element software DEFORM. Moreover, virtual orthogonal tests were proceeded to uncover several influence factors such as billet end taper, pressing speed and billet height. The results show that bulging can be effectively restrained in CEBU. In the condition of billet end taper α = 15°, pressing speed υ = 0.5 mm/s, and billet height h = 35 mm, a much smaller bulging can be achieved. The simulated results are in good agreement with experiment which was conducted with polycarbonate samples, and indicate CEBU is a promising method to control bulging in the upsetting of LHDR billet.

Keywords: upsetting, cone end billet, bulging, virtual orthogonal optimize, finite element method.

1. INTRODUCTION

Upsetting is widely used in hot forging to eliminate geometric defects, such as void and crack, in metals. It is generally accepted that the mechanical property of metals can be largely improved by upsetting. In upsetting, due to the friction effect between anvil and billet, metal flow around the billet end is largely constrained which leads to generating a rigid deformation zone in this region [1 – 3]. The rigid deformation zone not only affects the compaction ability of upsetting, but also leads to bulging [4, 5] and surface longitudinal cracks [6, 7], which seriously affect the forming quality of the billet. In particular, for the billet with height-diameter ratio above 2.0 which is generally named large height-diameter ratio (LHDR) billet, bulging is inevitably emerged after the traditional upsetting method [8]. Therefore, the traditional upsetting method should be revised to control bulging generation in the upsetting of LHDR billet.

Bulging is mostly related to the friction between anvil and billet in upsetting, and understanding this friction behaviour has attracted lots of effort from many researchers. Azushima studied the friction coefficient of the aluminium specimen with liquid lubrication in upsetting [9], which indicates this friction coefficient depends on forming reduction, and position at the contact interface. Based on results obtained from the upsetting test, Ching Lin investigated variation of the friction coefficient during upsetting using of an inverse algorithm [10]. Deng proposed a new friction testing method, the T-shape upsetting–extruding process employing a rectangular blank, for evaluating the friction conditions during the rib–web part forming process [11]. It was found that rib height and web width are both sensitive to friction conditions. Coppieters used the modified two specimen method (MTSM) and inverse method to identify the friction coefficient between tools and stacked circular specimens [12]. Meanwhile, many studies have been carried out to explore the characteristics and mechanism of bulging and longitudinal cracks generated on billet in upsetting. Hou proposed a computer program based on the upper-bound method to study the influence of workpiece geometry and friction [13]. Through hot compressing of cylindrical specimens with Gleeble tests and simulating with the finite element method, Tian demonstrated the bulging of specimens depends on the friction coefficient and temperature gradient [14]. Jenner established a thermo-plastic shear instability criterion for the onset of longitudinal cracking in upsetting, which provides a theoretical basis for experimental observations [15]. Besides that, to predict the effect of billet's height to diameter ratio and friction on the fracture initiation, Taguchi's optimization technique was applied for cylindrical upsetting by HariKrishna [16].

To effectively reduce the friction effect between anvil and billet, several new upsetting methods have been proposed. Concave billet upsetting (CBU) reduces the contact area between billet and anvil by prefabricating the billet end into a concave shape [17]. However, the concave forming process of the billet end is difficult to implement, which limits its application. Soft material pad upsetting (SMPU) is another effective method to reduce the rigid deformation zone around the billet end in upsetting [18]. By inserting soft metal between the billet end and anvil, the friction effect is dispersed in soft metal, and the forming uniformity of the billet is effectively improved. However, upsetting with a soft metal pad requires the consumption of soft metal, and it is impossible to eliminate the drum shape.

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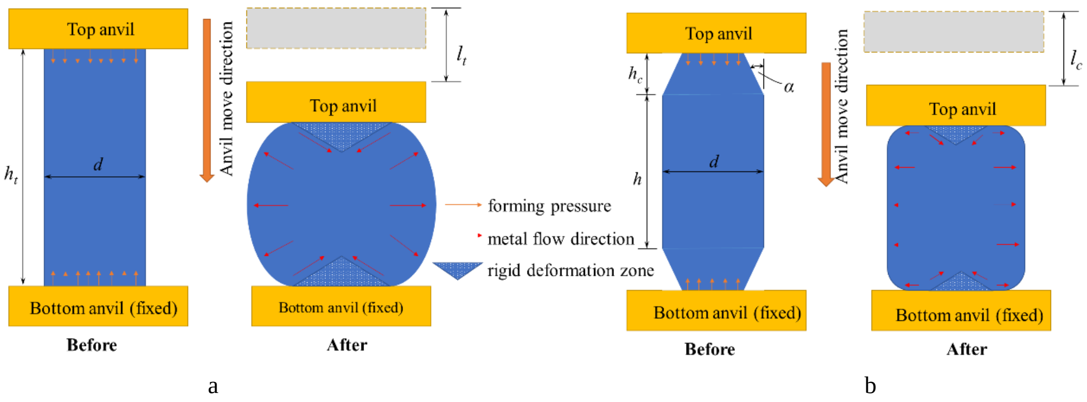

Fig. 1. Schematic of TU and CEBU: a – TU; b – CEBU

Besides that, stacking billet upsetting (SBU) is also proposed, but this method is prone to instability when dealing with LHDR billet. Although several new upsetting methods have been proposed to control bulging generation, all the previously mentioned methods suffer from some limitations. In addition, the number and solution of these new methods are not enough to suit various forming conditions.

As discussed above, refining friction condition is an essential and effective way to control bulging in upsetting, especially for LHDR billet. Meanwhile, the metal flow around the billet end should be considered to minimize the influence of the rigid deformation zone. In this article, a novel upsetting method named cone end billet upsetting (CEBU) is proposed. CEBU is featured by prefabricating the billet end into a cone shape, and aim to control bulging in the upsetting of the LHDR billet. The purpose of this study is to evaluate and validate CEBU in the upsetting of LHDR billet. Besides that, the optimized parameters of CEBU are achieved by virtual orthogonal tests to minimize bulging. The commercial finite element software DEFORM-3D was employed to analyse deformation characters and proceed with virtual orthogonal tests of LHDR billet with CEBU. In addition, the experiment was conducted with photoplastic material to verify the simulation results.

2. PRINCIPLE OF CONE END BILLET UPSETTING

The schematic of traditional upsetting (TU) is illustrated in Fig. 1 a. Due to the friction between anvils and billet, two large rigid deformation zones are formed at the ends of the billet in upsetting. This leads to metal flow ability around the billet end being very poor. Meanwhile, the metal flows non-uniformly from the billet centre to its surface. Consequently, bulging is formed at the middle of the billet, and longitudinal cracks are simultaneously generated on the billet surface.

The principle of CEBU is schematically shown in Fig. 1 b. By prefabricating a cone shape at the billet end, the contact area between the billet end and anvil is reduced. Compared with traditional upsetting, the metal flow in the cone region is greatly improved, which reduces the influence of the rigid deformation zone. In addition, a smaller rigid deformation zone leads to improving the uniformity of metal flow around the billet end. Finally, the bulging is largely restrained with CEBU, especially for LHDR billet.

3. FINITE ELEMENT ANALYSIS MODEL

The deformation characters of the LHDR billet with CEBU were analysed by the finite element method. The commercial finite element software DEFORM-3D was employed, and the established model in this software is shown in Fig. 2. Corresponding to the parameters illustrated in Fig. 1 b, their magnitudes in the analysed model are as follows: billet diameter d is 25 mm, height h is 50 mm, and cone angle α is 15°. Accordingly, the height-diameter ratio of the billet is 2.0 which can be categorized as an LHDR billet. The strain rate dependent elastic-plastic constitutive model was applied for billet, and the top and bottom anvils were all defined as a rigid body which means no deformation could be generated in upsetting. Material AISI-1015 was selected for billet from the material library of DEFORM-3D.

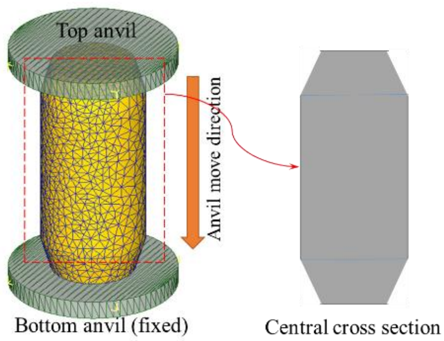

Fig. 2. Finite element analysis model

All the simulations were processed at room temperature. The bottom anvil was fixed, and the top anvil was moved vertically to the bottom anvil with a speed υ is 0.5 mm/s. A shear friction model with a factor of 0.03 was used to describe the friction behaviour between billet ends and anvils. The billet was divided by free quadrilateral meshes, and the initial number of meshes was set to 15000 in the software. Meanwhile, the adaptive remeshing technique was adopted to deal with unpredicted severe mesh distortion in simulation. At the end of the simulation, the upsetting reduction ration, which is represented by the ratio of the beginning and ending height of the billet, was reached 2.

4. SIMULATION RESULTS AND DISCUSSION

The deformation characteristics of billet in upsetting can be reflected by the variation of meshes. When the upsetting ratio is 2, the result of meshes variation on the billet central cross section is shown in Fig. 3. It can be seen from the result that metals in the cone zone flow toward the bevel of the cone in CEBU, which fills the shape vacancy of the cone region. Meanwhile, since the rigid deformation zone formed by CEBU is smaller, there is no bulging on the billet macroscopically.

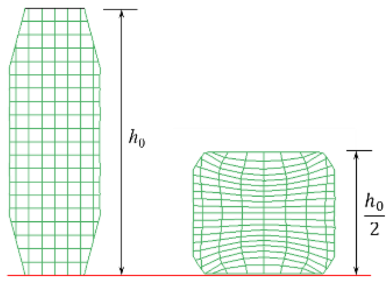

Fig. 3. Variation of meshes after upsetting

The evolution results of effective strain on the centre cross-section of billet during CEBU are shown in Fig. 4. The results show that with increasing upsetting reduction, the friction effect between the billet end and anvil gradually increases. However, due to the prefabricated cone shape at the billet end, the size of the rigid deformation zone largely depends on the diameter of the billet end is very small. Consequently, a large plastic deformation zone is formed around the billet end. With increasing upsetting reduction, the plastic deformation zones around billet ends are gradually approached and merged when the upsetting ratio reaches 2. At the end of the upsetting, the statistical results of equivalent strain for all nodes within the billet are illustrated in Fig. 5. According to the statistical results, a tiny part of the small equivalent strain which represents the rigid deformation zone has been achieved. Meanwhile, the equivalent strain distribution is more concentrated, indicating that a more uniform deformation can be realized by CEBU. As the results and discussion above, it can be deduced that CEBU can effectively control bulging Meanwhile, a more uniform deformation can be achieved which effectively prevent surface longitudinal cracks generation.

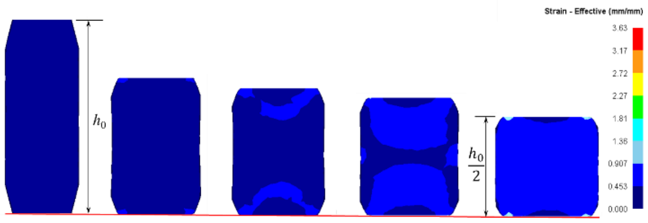

Fig. 4. Contour plot of equivalent strain in CEBU

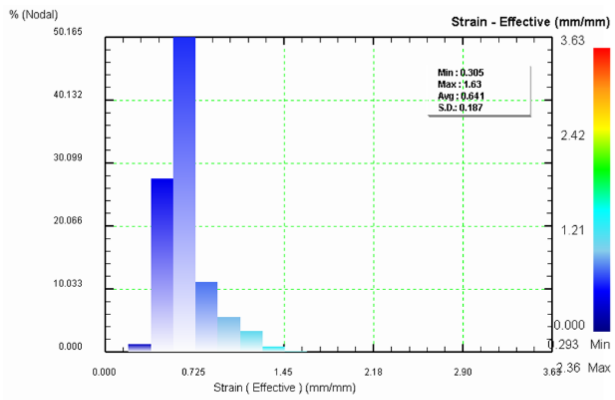

Fig. 5. Statistical results of the equivalent strain after CEBU

5. VIRTUAL ORTHOGONAL OPTIMIZE OF CEBU

Although the above simulation results have validated CEBU in control bulging, the optimized parameters should be obtained for further using. The virtual orthogonal method, which is successfully used to study influence parameters by finite element analysis [19, 20], was employed here. Billet end taper α, pressing speed υ and billet height h were selected as optimized parameters. Variations of the three parameters with 3 levels ($L_9(3^3)$) are listed in an orthogonal table as shown in Table.1.

Table 1. Parameters used in the virtual orthogonal test ($L_9(3^3)$)

Levels	Parameters		
	α, °	υ, mm/s	h, mm
1	45	0.5	30
2	30	1.0	35
3	15	1.5	40

Corresponding to the levels and parameters used in the virtual orthogonal test, nine simulations should be conducted independently. The three parameters used in these nine simulation models are listed in Table 2. Besides that, the same setting was used in the nine simulation models as proposed in section 2. Forming damage was also considered in this study [23, 24], so the three output results which are damage value, bulging size and equivalent strain were selected to identify the parameter combinations. The parameters and the corresponding simulation results of each simulation model are listed in Table 2.

Table 2. Parameters and results of the nine simulation models

Test No.	Parameters			Results		
	α, °	υ, mm/s	h, mm	Damage value	Bulging size, mm	Equivalent strain
1	45	0.5	30	0.218	31.499	1.52
2	45	1.0	35	0.238	33.211	1.15
3	45	1.5	40	0.251	34.504	1.16
4	30	0.5	40	0.233	33.038	1.57
5	30	1.0	35	0.264	33.925	1.55
6	30	1.5	30	0.282	34.828	1.28
7	15	0.5	35	0.200	34.555	2.31
8	15	1.0	30	0.193	34.893	2.90
9	15	1.5	40	0.277	35.148	2.39

To evaluate the multi-objective results, the queuing scoring method was employed. For each output parameter, its lowest and largest values were scored to 1 and 10 respectively. In addition, the other output parameters were scored by linear interpolation between the lowest and largest values. The scored values of each output parameter are listed in Table 3. Besides that, the score of virtual tests was obtained by the sum of the three scored values in each simulation.

Table 3. Results of each test by queuing scoring method

Test No.	Damage value	Bulging size /mm	Equivalent strain	Score
1	10.0	7.5	2.9	20.4
2	5.8	5.5	1.0	12.3
3	2.6	4.2	1.0	7.8
4	6.2	6.0	3.0	15.2
5	4.4	2.9	3.0	9.9
6	1.8	1.0	1.6	4.4
7	2.5	9.3	6.9	18.7
8	1.6	10.0	10.0	21.6
9	1.0	1.6	7.4	10.0

Based on the results listed in Table 3, the range analysis for multi-objective response values were proceeded. In range analysis, a smaller value means a lower influence on its response value at each factor level. In other words, the smaller value is, the better quality is. Table 4 is the range analysis results of queuing scoring. In Table 4, K_1, K_2 and K_3 represent the test scores of factor 1 level, factor 2 level and factor 3 level respectively. Accordingly, k_1, k_2 and k_3 represent the average test scores of factor 1 level, factor 2 level and factor 3 level, respectively. In addition, R is the range difference describing dispersion degree, which is the difference between the maximum and minimum average scores. According to the test scores, the optimal parameters of CEBU can be obtained as $\alpha = 15^{o}$, $\upsilon = 0.5$mm/s and $h = 40$ mm.

Table 4. Range analysis results of queuing scores

Factor level	Test scores		
	α	υ	h
K_1	40.5	54.3	42.7
K_2	29.5	43.8	30.9
K_3	50.3	22.2	46.7
k_1	13.5	18.1	14.2
k_2	9.8	14.6	10.3
k_3	16.8	7.4	15.6
R	7	10.7	5.3
Optimal parameters	$\alpha = 15^{o}$, $\upsilon = 0.5$mm/s, $h = 40$ mm		

The sum of average test scores of each parameter is able to reflect its influence on upsetting quality. According to the results listed in Table 4, the average test scores of these three parameters are illustrated shown in Fig. 6. The comparing results show that pressing speed υ is of the largest influence on upsetting quality with CEBU. Meanwhile, the influence of billet end taper α is greater than that of billet height h.

6. EXPERIMENT AND RESULTS

To validate the results of finite element analysis, experiments proceeded correspondingly. Samples were prepared with polycarbonate whose mechanical response is very close to steel and has been widely used to replace steel in experiments [21, 22].

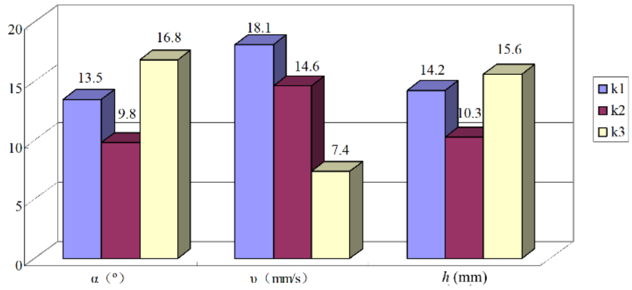

Fig. 6. Range distribution of upsetting parameters

All the samples were prefabricated into a cylinder with height and diameter are 50 mm and 25 mm respectively. In addition, all the billet ends were cut into a cone shape. Then, the samples were polished and annealed at 170 ℃ to eliminate the residual stress within it. Finally, all the samples were upset by WDW-200 electronic testing machine at room temperature with the same upsetting ratio of 2.0. The same friction condition was applied for all the tests. The experiment parameters were derived from the virtual orthogonal test, which values are listed in Table 5.

Table 5. Upsetting parameters used in experiments

Sample	h, mm	υ, mm/s	α, °
a	40	1.5	30
b	40	0.5	30
c	35	1.0	30
d	30	1.5	15
e	30	1.0	15
f	35	0.5	15

The shapes of samples after upsetting are shown in Fig. 7.

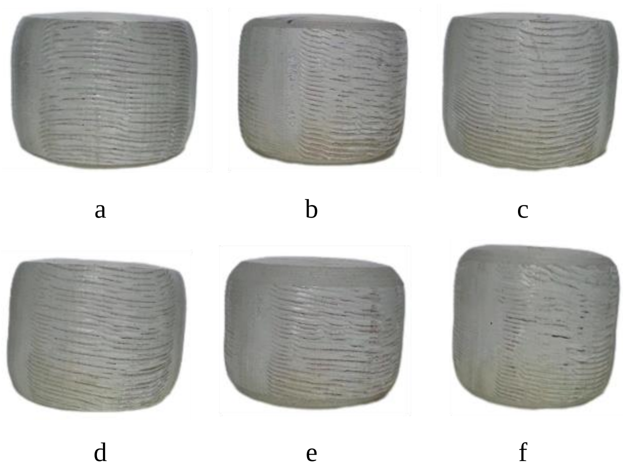

Fig. 7. The shape of samples after upsetting

Obviously, a small bulging has been achieved in all the samples. In addition, parallel longitudinal lines are generated on the sample surface, which indicates a more uniform deformation is obtained in CEBU. The diameters of sample middle and end were measured, and its value are illustrated in Fig. 8. The comparing results show that bulging in sample *b* and *e* are smaller than in others. It is consistent with the optimized results by virtual orthogonal tests, which validates the finite element analysis results.

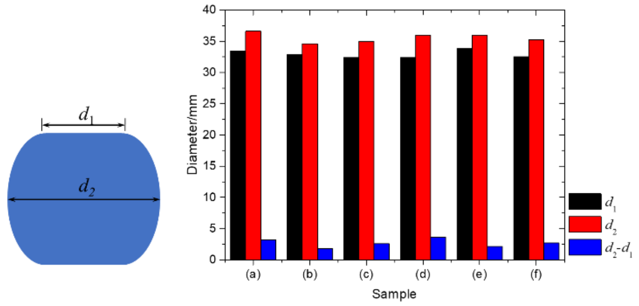

Fig. 8. Measurement results of sample diameter

7. CONCLUSIONS

A novel upsetting method named cone end billet upsetting (CEBU) is proposed in this article, to restrain bulging in upsetting of large height-diameter ratio (LHDR) billet. The finite element analysis results show that CEBU can effectively reduce bulging, and the deformation uniformity in upsetting is greatly improved simultaneously. The influence parameters of CEBU were analyzed and optimized by a virtual orthogonal test, and the optimal parameters were obtained as $\alpha = 15°$, $\upsilon = 0.5$ mm/s, $h = 40$ mm. The simulations were verified by experiments with polycarbonate samples. This study shows that CEBU is a promising method to control bulging in the upsetting of LHDR billet, which can be effectively used in the upsetting of metal parts used in small size precision machine.

Acknowledgments

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