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Effects of stretching processing parameters on the mean elongation ratio and maximum spread ratio of heavy forgings

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Abstract Heavy forgings are the essential parts of some nuclear, electrical power generation, rolling mill equipments. The rigid-viscoplastic finite element models (FEM) were established to study the effects of processing parameters (deformation degree, tool width ratio, blank width ratio, strain rate, friction, and forming temperature) on the mean elongation ratio and maximum spread ratio of heavy forgings during stretching process. A new formula (LD model) is proposed to predict the mean elongation ratio for stretched heavy forgings. The predicting capabilities of LD model were verified by experiments. Results show that: (1) The mean elongation ratio and maximum spread ratio increase with the increase of deformation degree; (2) When the tool width ratio is decreased, the mean elongation ratio increases and the maximum spread ratio decreases; (3) When the blank width ratio is increased, the mean elongation ratio increase and the maximum spread ratio decrease; (4) The mean elongation ratio is not affected by strain rate, friction, and forming temperature. However, the effects of these three process parameters on the maximum spread ratio of deformed block are significant; (5) There is a good agreement between the experimental results and predictions by LD model, which confirms that the proposed LD model is valid for the practical industrial productions.

Introduction

Heavy forgings, which are usually obtained by forging ingots directly, are the essential parts of nuclear, electrical power generation, rolling mill equipments. Therefore, the sizes of steel ingots has become remarkably large in order to keep up with an increase in the size of such heavy forgings as round steel bar, rotor shaft, roll shaft, cylinder, and square steel block and so on. Usually, the open-die forging processes, including the upsetting and stretching, are the main free forging methods of heavy forgings. The workpiece is manipulated manually and shaped under a hammering action with hot or cold-working conditions. The hot forging of a metal occurs when the metal is deformed plastically above its recrystallization temperature and usually involves severe geometrical changes from an initially simple geometry [1–4]. For heavy forgings, the programming of an open-die forging process can be accomplished with a press and manipulator, as shown in Fig. 1. However, this requires accurate and rapid theoretical analysis. So, accurate predictions of the shapes of deformed forgings or blocks are becoming more and more important. There are some researches reporting the deformation pattern in open-die forging [5–10]. Aksakal et al. [5] minimized the total power consumption at each increment, and so the load was determined and the prediction of metal flow was evaluated. Kudo [6] presented a procedure to facilitate the analysis of complicated problems for plane strain forming operations by introducing the concept of a 'unit rectangular deforming region'. Baraya and Johnson

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Fig. 1 An open-die forging process with huge manipulator (① Press; ② Manipulator; ③ Heavy forging)

[7] analyzed bar-forging using the upper-bound technique. Three solutions were suggested through triangular velocity fields, for each of which the power dissipation and load were determined for three different metals. Safar and Juneja [8] introduced work on the problem of determining load requirements by taking bulging into account. Braun-Angot and Berger [9] presented work which dealt with an upper-bound solution for spread and pressure. A long rectangular bar was compressed by an opposed pair of flat tools. However, more detailed analysis and discussion about the effects of the forging processing parameters on the mean elongation ratio and maximum spread ratio of heavy forgings during stretching process should be carried out. Kanacri et al. [10] investigated the compression of rectangular blocks between two parallel platens.

In this study, the thermo-mechanical coupled finite element models were established to study the effects of processing parameters on the mean elongation ratio and maximum spread ratio of heavy forgings during stretching process. The considered forging processing parameters include the deformation degree, tool width ratio, blank width ratio, strain rate, friction, and forming temperature. Then, a new formula is proposed to predict the mean elongation ratio for the stretched forgings or blocks. The predicting capabilities of LD model were verified by experiments.

Fundamental principle of the rigid-viscoplastic FEM

Generally, finite element method is one effective ways to analysis the deformation of forgings [11, 12]. The rigid-viscoplastic FEM is based on the rigid-viscoplastic variation principle. Usually, the governing equations for the solution of the mechanics of rigid-viscoplastic deformation do not consider the volume force and neglect the elastic deformation of the material, and satisfy the equilibrium equation, the geometrical equation, volume constancy, and the material conforming to Mises Yield criterion. Using the penalty function method to handle the condition of volume constancy, the energy function is expressed as follows:

$$\phi = \int \sigma\dot{\bar{\varepsilon}}\,\mathrm{d}V + \frac{\alpha}{2}\int \left(\dot{\varepsilon}_V\right)^2\mathrm{d}V - \int\limits_{S_T} F_i u_i\,\mathrm{d}S \qquad (1)$$

in which σ, $\dot{\bar{\varepsilon}}$, $\dot{\varepsilon}_V$, α, and F_i are the effective stress, effective strain rate, volume strain rate, penalty constant, and external force, respectively. u_i is the velocity at the surface S_T and S_T is the area of the surface acted upon by the external force.

In this study, the rigid-viscoplastic finite element models were established to study the effects of processing parameters on the mean elongation ratio and maximum spread ratio of heavy forgings or blocks with rectangular section during stretching process, as shown in Fig. 2. Among the models, the forging processing parameters, including the deformation degree, tool width ratio, blank width ratio, strain rate, friction, and forming temperature, were considered. The

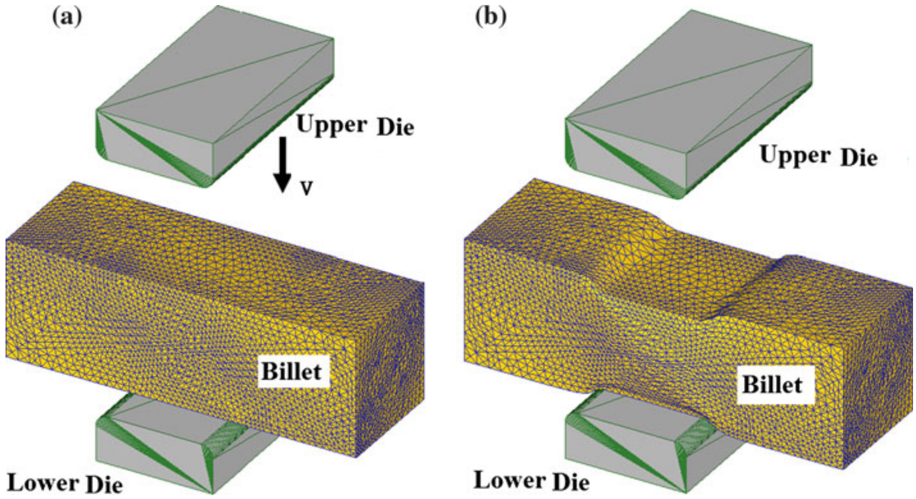

Fig. 2 The meshed finite element model: **a** initial billet; **b** deformed block

used material is 42CrMo high-strength low alloy steel, whose properties were reported by the authors [13–16]. The process conditions in finite element analysis and some thermal physical properties of deformed block are: (1) The deformation degree varies from 0 to 20% with a interval of 5%; (2) The tool width ratio varies from 0.5 to 1.0 with a interval of 0.1; (3) The blank width ratio varies from 0.6 to 2.0 with a interval of 0.2; (4) The strain rate varies from 0.01 to 0.07 s^{-1} with a interval of 0.02 s^{-1}; (5) The friction coefficient between block and tool varies from 0.1 to 0.7 with a interval of 0.2; (6) The temperature of environment is assumed as the room temperature, while the billets are heated to 1000, 1100, and 1200 °C, respectively, before the stretching experiments; (7) The convection coefficient to environment is 0.02 N/(s mm °C), and the heat transfer coefficient between deformed block and tool is 5 N/(s mm °C); (8) The pressing velocity is 15 mm/s.

Experiments

According to the forging process parameters studied in finite element models, a number of stretching experiments were carried out to compare and validate the theoretical analysis. A commercial 42CrMo high-strength steel of compositions (wt%) 0.450C–0.280Si–0.960Cr–0.630Mn–0.190Mo–0.016P–0.012S–0.014Cu–(bal.)Fe was used in this investigation. The stretching tests were conducted between flat anvils or tools of 3000 kN hydraulic press for the blocks with rectangular section, as shown in Fig. 3. A range of different tool width ratios and blank width ratios were designed, and the temperatures of the workpiece vary from 900 to 1200 °C.

Results and discussion

Generally, heavy forgings should not only meet geometrical requirements, but also have superior mechanical properties and fine grain distribution. Due to the large size and weight of the heavy forgings, for example, the forging with the length of over 19 m and the weight of more than 450 tons, the open-die forging is obviously the best way to accomplish the make of heavy forgings by means of the forging manipulators, as shown in Fig. 1. In order to carry out the roboticized forming of heavy forgings, the optimal moving trajectory should be provided for forging manipulators. In the planning of manipulators' moving trajectory, the mean elongation ratio and maximum spread ratio of heavy forgings are the most important parameters. So, the effects of stretching processing parameters on the mean elongation ratio and maximum spread ratio of heavy forgings should be discussed in details.

In this section, the effects of processing parameters, including the deformation degree, tool width ratio, blank width ratio, strain rate, friction, and forming temperature, on the mean elongation ratio and maximum spread ratio of the stretched heavy forgings are discussed by finite element analysis (FEA). Based on the results of FEA, a new formula (LD model) is proposed to predict the mean elongation ratio for heavy forgings during stretching process. Figure 4 shows the dimensions of billet, die, and deformed zone of the billet. Then, the deformation degree, tool width ratio, and blank width ratio can be expressed as $(h_0 - h_1)/h_0$, b/h_0, and w_0/h_0, respectively. The mean elongation ratio (e_{mean}) can be defined as,

$$e_{\text{mean}} = \frac{\Delta l}{l_0} = \frac{l_1 - l_0}{l_0} = \frac{l_1 - b}{b} \quad (2)$$

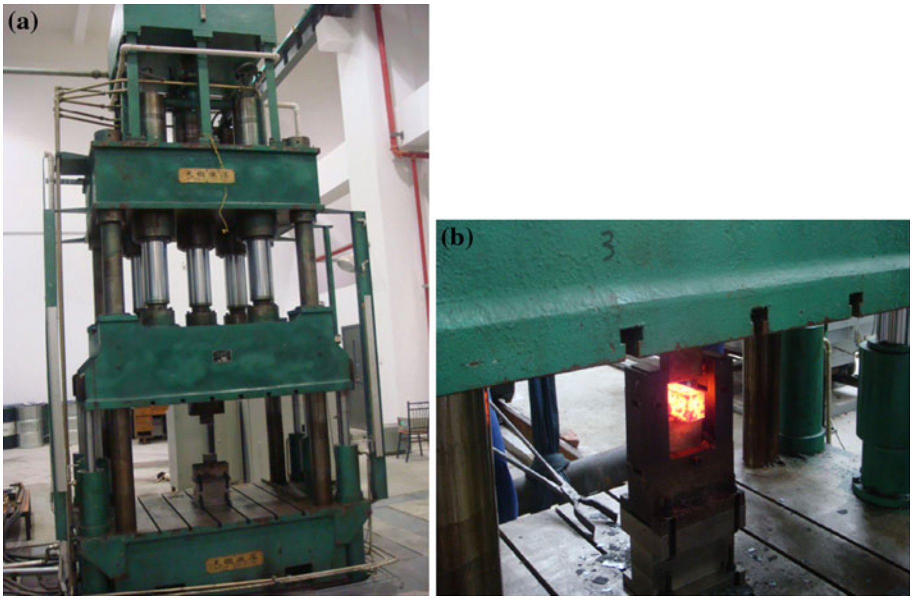

Fig. 3 Experiments: **a** 3000 kN hydraulic press; **b** the deformed block with rectangular section

The maximum spread ratio ($s_{\max}$) can be defined as,

$$s_{\max} = \frac{w_{\max} - w_0}{w_0} \quad (3)$$

Effects of forging processing parameters on the deformation of heavy forgings

Effects of deformation degree

Figure 5 shows the effects of deformation degree on the mean elongation ratio and maximum spread ratio of deformed block. It can be found that the mean elongation ratio and maximum spread ratio increase with the increase of deformation degree. When the deformation degree is 20%, the mean elongation ratio and maximum spread ratio reach 0.1621 and 0.0892, respectively. This is determined by the principle of constant and incompressible volume during the stretching deformation.

Effects of tool width ratio

Figure 6 shows the effects of tool width ratio on the mean elongation ratio and maximum spread ratio of deformed block. Figure 6a indicates that the effects of the tool width ratio on the mean elongation ratio are not obvious when the deformation degree is less than about 8%. However, the mean elongation ratio increases with the decrease of tool width ratio when the deformation degree is more than about 8%. Furthermore, the larger deformation degree, the

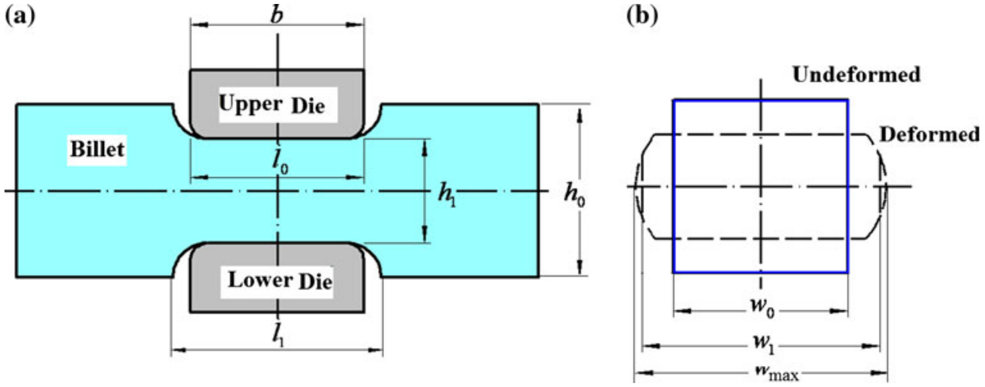

Fig. 4 Dimensions of **a** billet and die; **b** deformed and undeformed zone of billet

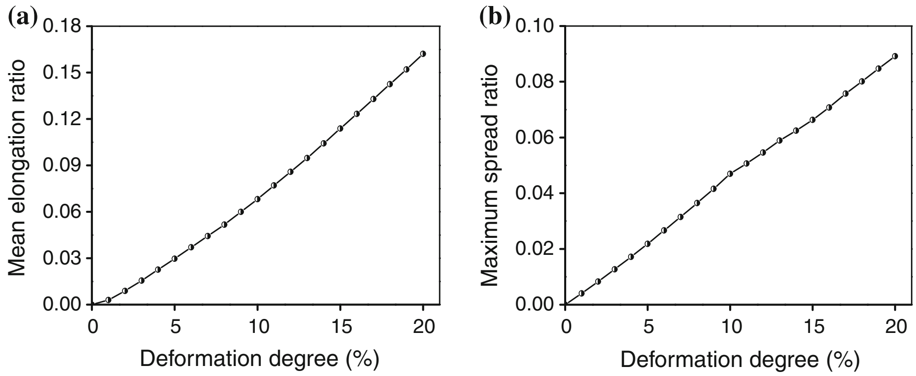

Fig. 5 Effects of deformation degree on **a** mean elongation ratio and **b** maximum spread ratio (tool width ratio is 0.8, blank width ratio is 1.0, friction of tool/block is 0.3, deformation temperature is 1200 °C, and strain rate is 0.03 s^{-1})

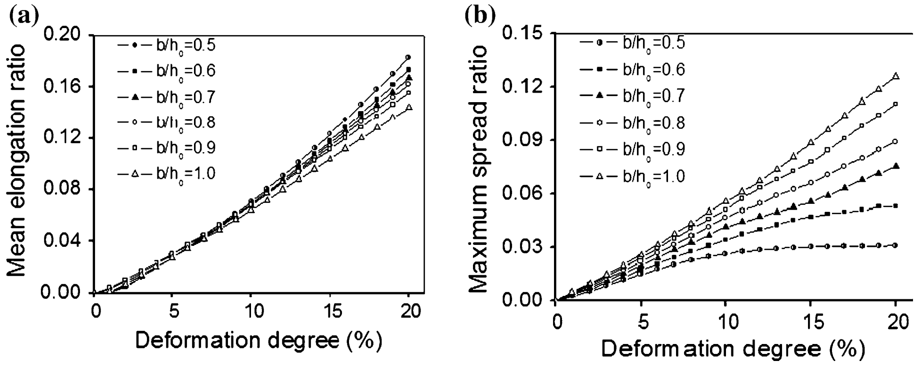

Fig. 6 Effects of tool width ratio on **a** mean elongation ratio and **b** maximum spread ratio (blank width ratio is 0.8, friction of tool/block is 0.3, deformation temperature is 1200 °C, and strain rate is 0.03 s^{-1})

faster the increase of elongation ratio for a constant change of tool width ratio. For example, when the tool width is changed from 0.5 to 1.0, the increments of the elongation ratio are 0.0096 and 0.0388 for the cases with deformation degree of 15 and 20%, respectively. From Fig. 6b, it can be found that the maximum spread ratio increases with the increase of tool width ratio. The larger deformation degree, the bigger the increment of the maximum spread ratio for a constant change of tool width ratio.

Figure 7 shows the effects of tool width ratio on the material moving in the deformed zone of heavy forgings. The arrowheads indicate the directions of the material moving. Obviously, more and more deformed materials move into sideways spread with the increase of tool width ratio, which makes the spread ratio (including maximum spread ratio) increase with the increase of tool width ratio. So, the spread ratio is the measure of the proportion of the deformed material moving into sideways spread. If the spread ratio is zero, there will no side-spread, only elongation. However, for the industrial production, the spread ratio is not zero and significantly by tool width ratio. According to the constant and incompressible volume principles of the deformed block, the deformed material moving into axial direction becomes less and less with the increase of the tool width ratio. Therefore, the mean elongation ratio decreases with the increase of tool width ratio.

Effects of blank width ratio

Figure 8 shows the effects of blank width ratio on the mean elongation ratio and maximum spread ratio of deformed block. Figure 8a indicates that the effects of blank width ratio on the mean elongation ratio are not obvious when the deformation degree is less than about 5%. However, the mean elongation ratio increases with the increase of blank width ratio when the deformation degree is more than about 5%. The larger deformation degree, the faster the increase of the elongation ratio for a constant change of blank width ratio. From Fig. 8b, it can be found that the maximum spread ratio decreases with the increase of the tool width ratio. The larger deformation degree, the bigger the decrement of the maximum spread ratio for a constant change of blank width ratio.

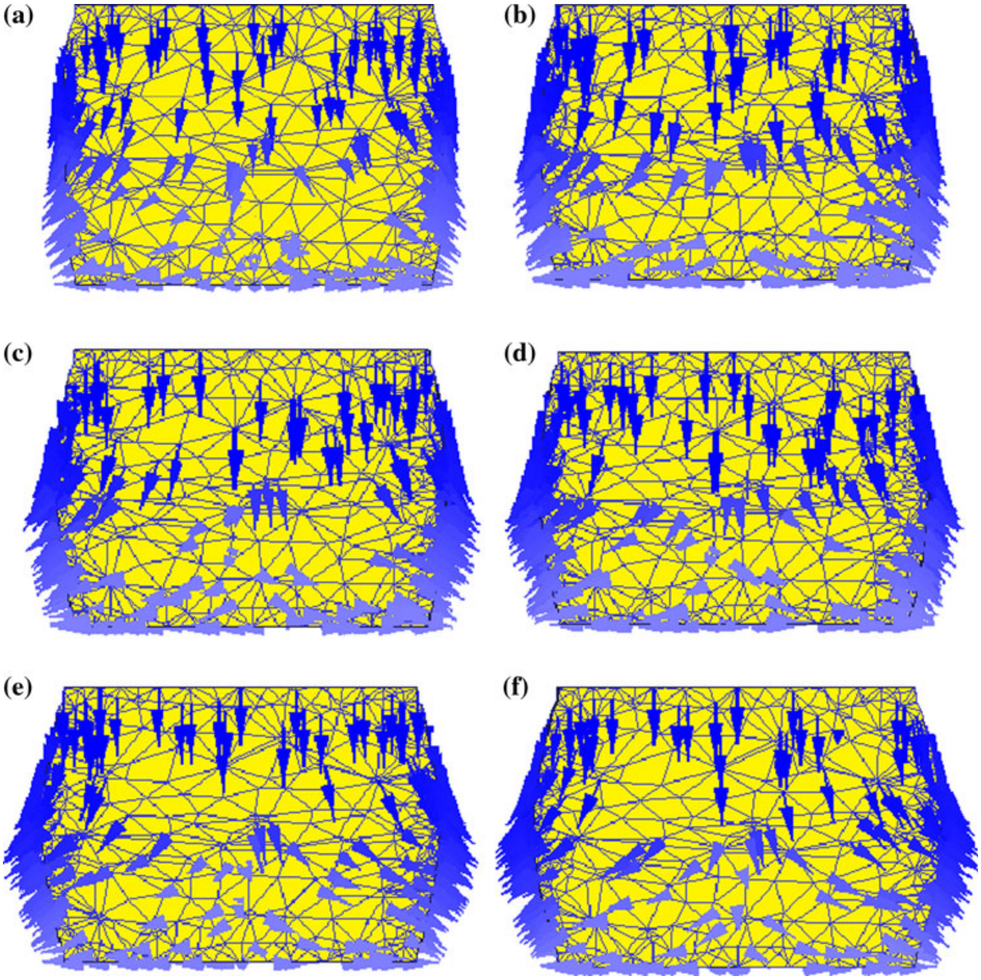

Fig. 7 Moving of the material in deformed zone with tool width ratio of **a** 0.5; **b** 0.6; **c** 0.7; **d** 0.8; **e** 0.9; **f** 1.0

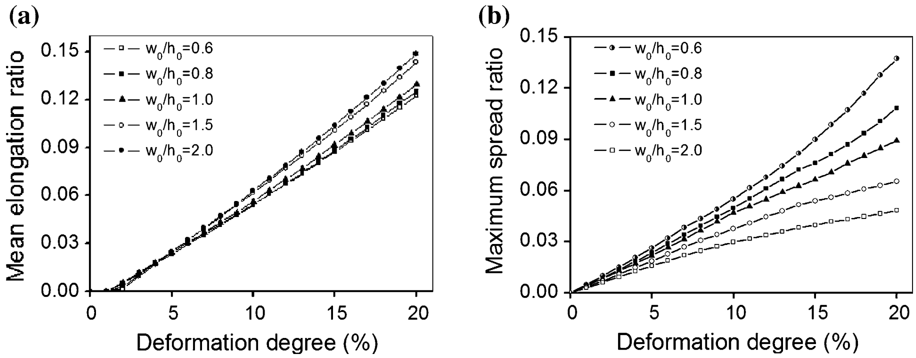

Fig. 8 Effects of blank width ratio on **a** mean elongation ratio and **b** maximum spread ratio (tool width ratio is 1.0, friction of tool/block is 0.3, deformation temperature is 1200 °C, strain rate is 0.03 s^{-1}, and deformation degree is 20%)

Figure 9 shows the effects of blank width ratio on the material moving in the deformed zone of heavy forgings. The arrowheads also indicate the directions of the material moving. The number of the arrows denotes the intensity of the material moving. I t can be found that the intensity of the lateral material moving becomes smaller and smaller with the increase of blank width ratio, which indicates that the deformed material moving into sideways spread becomes less and less. So, the maximum spread ratio decreases with the increase of blank width ratio. According to constant and incompressible volume principles of the deformed block, the deformed material moving into axial direction becomes more and more with the increase of blank width ratio. Therefore, the mean elongation ratio increases when the blank width ratios are increased.

Effects of strain rate, friction, and temperature

Figures 10 and 11 show the effects of strain rate, friction, and temperature on the mean elongation ratio and maximum spread ratio of deformed block, respectively. Obviously, the mean elongation ratio is almost not affected by the strain rate, friction and forming temperature. However, the effects of these three process parameters on the maximum spread ratio of deformed block are significant. The maximum spread ratio increases with the increase of temperature and friction of tool/block. However, the increase of strain rate will decrease the maximum spread ratio. This is because the given tool width ratio, blank width ratio, and deformation degree determine the size of the deformed zone of the block. Then, the axial moving of the material is restricted by the two rigid end of the block, while the lateral boundary of the deformed zone is relatively free. So, the deformed material mainly moving into sideways spread, which results the effects of strain rate, friction, and forming temperature on the maximum spread ratio of the deformed block are significant.

A new formula for predicting mean elongation ratio of heavy forgings

The first pioneering work in bar-forging analysis was introduced by Tomlinson and Stringer [17], who developed an empirical equation (TS model) for the prediction of elongation. The TS model can be expressed as,

$$w_1 = w_0\left(\frac{h_0}{h_1}\right)^S \tag{4}$$

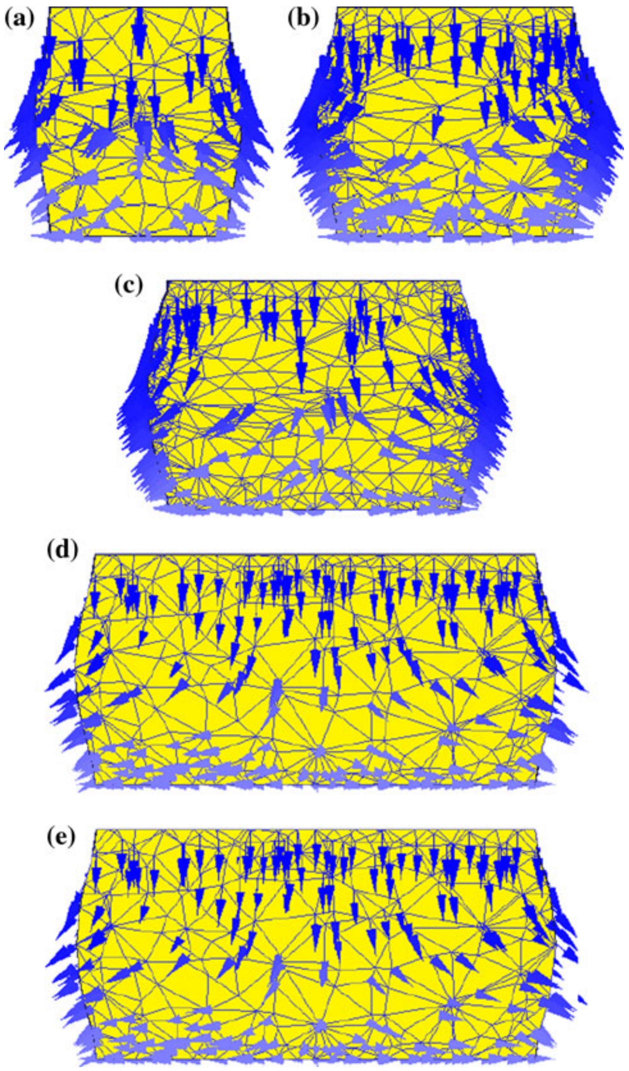

Fig. 9 Moving of the material in deformed zone with blank width ratio of **a** 0.6; **b** 0.8; **c** 1.0; **d** 1.5; **e** 2.0

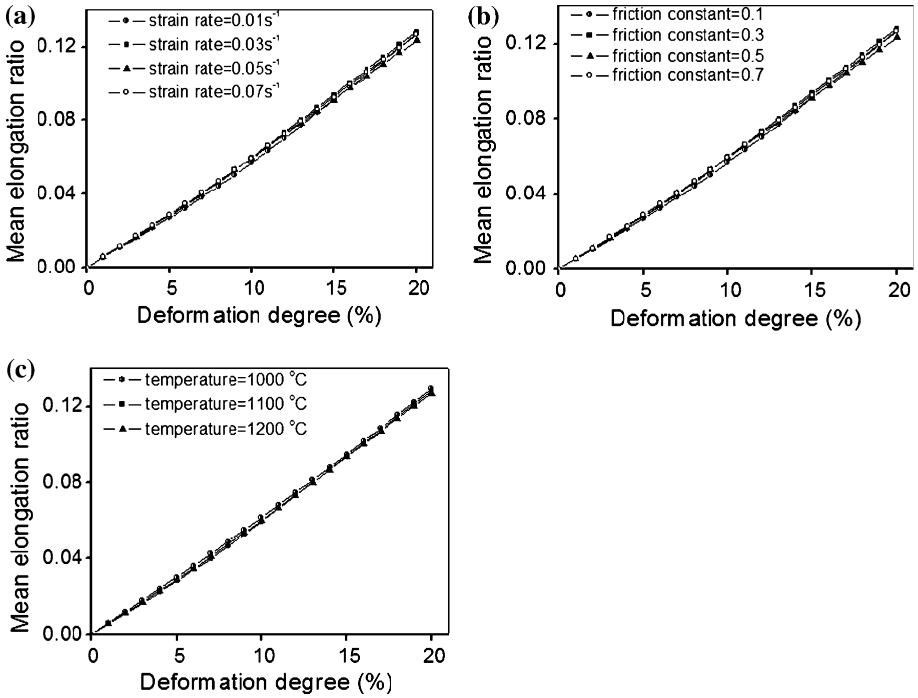

Fig. 10 Effects of **a** strain rate, **b** friction, and **c** temperature on mean elongation ratio (tool width ratio is 1.0, blank width ratio is 0.8, and deformation degree is 20%)

$$l_1 = l_0\left(\frac{h_0}{h_1}\right)^{1-S} \tag{5}$$

$$s = 0.29 - 0.16\frac{h_1}{h_0} + 0.343\frac{b}{w_0} - 0.048\left(\frac{b}{w_0}\right)^2 \tag{6}$$

where s is coefficient of spread, the physical meanings of the parameters are indicated in Fig. 4.

Based on the results of finite element analysis, a new formula (called as LD model) is proposed by fitting method, to predict the mean elongation ratio of heavy forgings during the stretching process. The LD model can be expressed as,

$$\begin{aligned} e_{\text{mean}} = {} & \left(\frac{\Delta h}{h_0}\right)^2\left(2.0672 - 2.1303\frac{b}{h_0} + 0.5510\frac{w_0}{h_0}\right. \\ & \left. + 0.2555\frac{b}{h_0}\frac{w_0}{h_0}\right) + \left(\frac{\Delta h}{h_0}\right)\left(0.4453 + 0.0418\frac{b}{h_0}\right. \\ & \left. + 0.1216\frac{w_0}{h_0} - 0.0232\frac{b}{h_0}\frac{w_0}{h_0}\right) \end{aligned} \tag{7}$$

Figure 12 shows the comparisons between the experimentally measured and predicted mean elongation ratio by LD model (Eq. 7), TS model. From Fig. 12a, it can be found that there are some differences between the experimental results and predicted ones by LD model, TS model. So, based on the experimental results, the proposed LD model needs to be further improved as,

$$\begin{aligned} e_{\text{mean}} = {} & \left(\frac{\Delta h}{h_0}\right)^2\left(1.7672 - 2.1303\frac{b}{h_0} + 0.5510\frac{w_0}{h_0}\right. \\ & \left. + 0.2555\frac{b}{h_0}\frac{w_0}{h_0}\right) + \left(\frac{\Delta h}{h_0}\right)\left(0.4453 + 0.0418\frac{b}{h_0}\right. \\ & \left. + 0.1216\frac{w_0}{h_0} - 0.0232\frac{b}{h_0}\frac{w_0}{h_0}\right) \end{aligned} \tag{8}$$

Figure 12b indicates that the experimental results are in a good agreement with the predicted ones by the improved LD model (Eq. 8), and the predicting capability of LD model is better than that of TS model. So, LD model can be used for predicting the mean elongation ratio of heavy forgings during the stretching process in industrial productions.

Conclusion

The effects of deformation degree, tool width ratio, blank width ratio, strain rate, friction, and forming temperature on the mean elongation ratio and maximum spread ratio of the stretched heavy forgings are investigated. A new formula (LD model) is proposed to predict the mean elongation ratio for the stretched heavy forgings. It can be found that the deformation degree, tool width ratio, and blank width ratio significantly affects the mean elongation ratio and maximum spread ratio of the stretched heavy forgings,

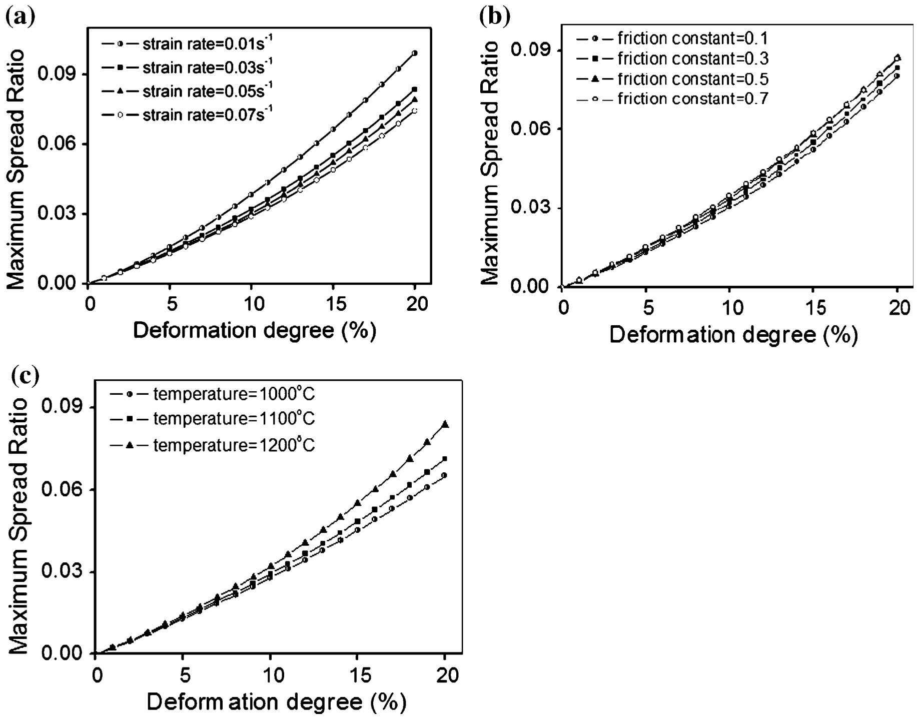

Fig. 11 Effects of **a** strain rate, **b** friction, and **c** temperature on the maximum spread ratio (tool width ratio is 1.0, blank width ratio is 0.8, and deformation degree is 20%)

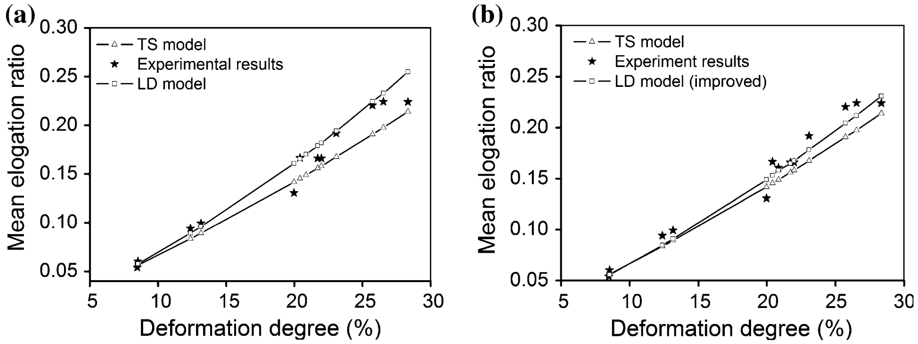

Fig. 12 Comparisons between the experimentally measured and predicted mean elongation ratio by LD model, TS model

and the effects of strain rate, friction, and temperature on the maximum spread ratio of deformed block are obvious. However, the mean elongation ratio is not affected by the strain rate, friction, and temperature. A good agreement between the experimental results and predictions by LD model indicates that the proposed LD model is valid for the practice industrial productions.

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