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ORIGINAL ARTICLE

Deformation characteristics of transitional region during local loading forming of Ti-alloy rib-web component on the double-action press

Pengfei Gao [1] · Zhenfang Liu [1] · Zhenni Lei [1]

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Abstract It may be a potential way to realize high-efficiency and high-quality local loading forming on the double-action press. However, the deformation characteristics and forming quality of transitional region are the weak link during forming process. In this work, the material flow, deformation inhomogeneity, forming defect of transitional region, and their dependences on the local loading parameters were quantitatively investigated by FE simulation. It is found that due to the constraint clearance, the web material would undergo twice transverse flow with opposite directions successively in two loading steps. This phenomen is basically the same as that in the local loading forming on single-action press, while the extent of transverse material flow on double-action press is greatly smaller. Finally, the transitional region presents different strain distributions in various sub-regions. Region A and region C present a symmetric strain concentration area at rib root, while region B presents a slant strain concentration area at the middle rib. The forming quality on double-action press is better than that on the single-action press. Only a cavum defect at left rib is produced because of the transverse material flow. Constraint clearance plays the most important role in the deformation characteristics and forming quality during the local loading forming on double-action press. The transverse material flow and cavum defect can be suppressed by decreasing the constraint clearance, but the deformation inhomogeneity would increase to some extent at the same time. In addition, the friction factor and radius of left rib are the second significant factors. Increasing the friction factor and radius of left rib is helpful to suppress the transverse material flow and cavum defect, respectively. As far as the forming quality of transitional region is concerned, it is a better way to conduct the local loading forming on double-action press than on single-action press. The results will provide basis for the design of processing parameters in the local loading forming of Ti-alloy rib-web component on double-action press.

Keywords Local loading forming · Double-action press · Transitional region · Deformation characteristics

✉ Pengfei Gao
gaopengfei@nwpu.edu.cn

[1] State Key Laboratory of Solidification Processing, School of Materials Science and Engineering, Northwestern Polytechnical University, P.O. Box 542, Xi'an 710072, People's Republic of China

1 Introduction

The titanium alloy components with complex shape and specific performance have been widely used in aerospace field to satisfy the ever increasing demands of high performance and light weight in aircrafts. However, it is difficult to form these components due to the high yield stress and low ductility of titanium alloy, complex structure, and high forming requirements. To solve this challenge, Yang et al. [1–4] proposed an innovative isothermal local loading forming technology, which integrates the characteristics of the isothermal forming and local loading forming. During local loading forming, the upper die is separated into several parts, and only partial die presses in each loading step. The local loading is achieved by controlling the movement of blocked dies, while the movement control methods are different for different equipment. For the single-action press, the relative position between blocked dies is adjusted by a spacer block, as shown in Fig. 1 a, b. For the double-action press, the movement of each blocked die is controlled independently, as shown in Fig. 1 c [5, 6]. The isothermal local loading forming can effectively reduce the forming load, enlarge forming size, and control the material flow, providing a feasible way to manufacture these components.

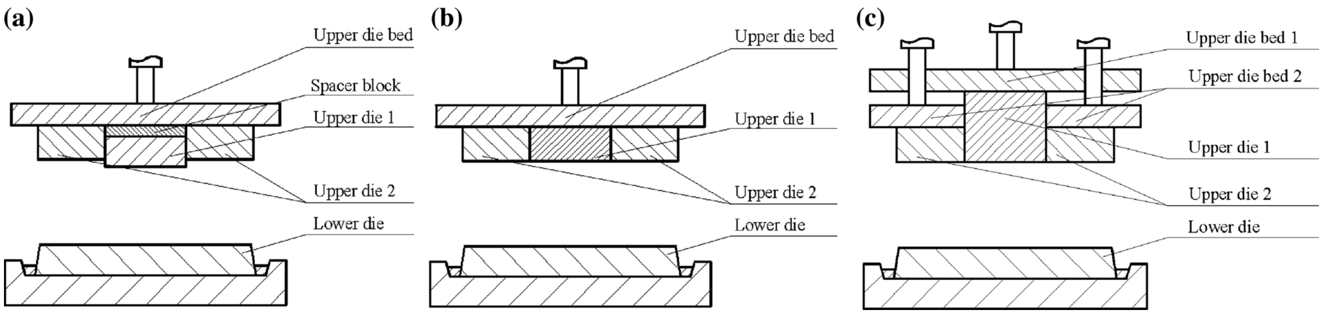

Fig. 1 Illustration of local loading forming on different equipment [6]. **a** The first loading step on single-action press. **b** The second loading step on single-action press. **c** Double-action press

However, the isothermal local loading forming is a complicated process with coupling effects of multi-die and multi-parameters, which makes the forming process very complex and difficult to control. Especially, the transitional region, i.e., the region near die partitioning, deforms under the constraints of loading region and unloading region, whose deformation and material flow are very inhomogeneous and complex. This makes it more prone to produce forming defects such as folding, underfilling, and nonuniform microstructure than other regions, becoming the weak link of local loading forming [7–9]. Consequently, it needs more concerns on the deformation characteristics of transitional region during local loading forming.

At present, the isothermal local loading forming is mainly conducted on the single-action press due to its low equipment cost. And, systematic works have been carried out on the deformation characteristics of transitional region under this condition. Gao et al. [10] quantitatively investigated the rule of material flow in transitional region by FE simulation and found that twice transverse material flow with opposite directions occurred in the first and second loading steps sequentially. Zhang and Yang [11] further investigated the distribution of material flowing from loading region into unloading region during local loading forming. They also developed a prediction model for fast analyzing the material flow and cavity fill in local loading process of multi-rib component using the slab method [12]. Meanwhile, the deformation inhomogeneity of transitional region was also quantitatively evaluated and analyzed [13]. It is found that the deformation inhomogeneity of transitional region is essentially caused by two kinds of strain concentration areas and strongly dependent on the die parameters. Gao et al. [10, 14] found that the folding and cavum defects are usually produced in the transitional region. Then, they studied the effects of local loading parameters on the formation of forming defects in transitional region and developed the prediction models of forming defects under various structural parameters [15]. Combining with the prediction models of forming defects, Gao et al. [16] determined the process window considering forming defects of transitional region through the stepwise searching method. However, the operation of local loading forming on single-action press is difficult and time-consuming. After each loading step, the workpiece must be cooled and taken out to adjust the relative position of blocked dies, which leads to more heating number and longer production cycle. Conversely, the double-action press can easily adjust the relative position of blocked dies. As a result, it may be a potential way to realize high-efficiency and high-quality local loading forming on the double-action press. By now, only primary investigations have been conducted on the local loading forming on double-action press. Sun et al. [17] studied the effect of preform billet on filling quality of a bulk-head in the isothermal local loading forming on double-action press. They also studied the effects of loading parameters on the filling and damage in the same forming process [18]. However, there is still a lack of studies on the deformation characteristics and forming quality of transitional region, which is the key region in local loading forming. Therefore, further investigation is required to reveal the material flow, uneven deformation and forming defects of transitional region during the local loading forming of large-scale rib-web component on double-action press.

In this paper, the material flow, deformation inhomogeneity, and forming defects of transitional region in the local loading forming on double-action press were analyzed and compared to those conducted on the single-action press. In addition, the effects of processing parameters (local loading parameters and die parameters) on the deformation characteristics of transitional region on double-action press were studied. The results will deepen our understanding on the deformation characteristics of transitional region and provide guidance for the design of processing parameters during isothermal local loading forming of Ti-alloy rib-web component on the double-action press.

2 Research methodology

2.1 FE model of transitional region

FE simulation has become an important tool to predict and analyze the distribution of strain and velocity, and the

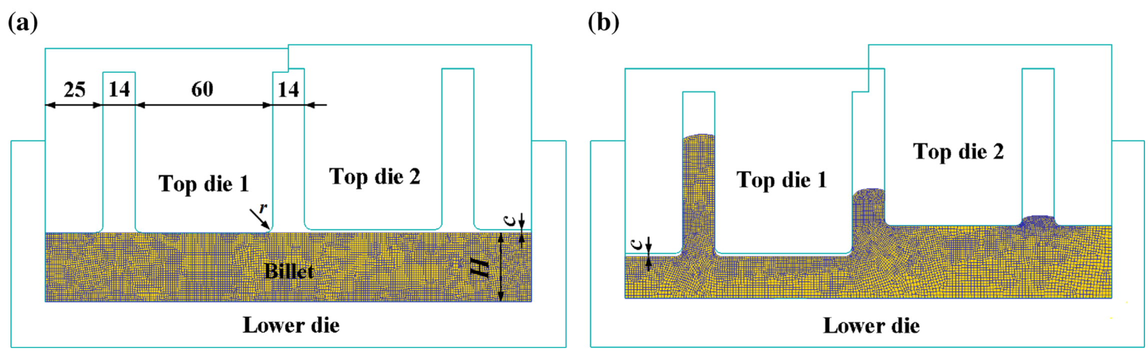

Fig. 2 FE model of transitional region in the local loading forming of large-scale rib-web component on double-action press. **a** The first loading step. **b** The second loading step

evolution of defects during forging process [19–22]. The authors have developed and validated the FE model of transitional region in the local loading forming of rib-web component, as shown in Fig. 2. By the FE model, the deformation characteristics of transitional region during local loading forming on single-action press have been analyzed successfully [10, 13–16]. So, this model was also applied in this work to study the deformation characteristics of transitional region on double-action press. As shown in Fig. 2, the top die is divided into two symmetrical parts: top die 1 and top die 2.The local loading forming is conducted in two loading steps. In the first loading step, top die 1 is loaded while the top die 2 put a constraint to the unloaded area. In the second local loading step, top die 2 is loaded and top die 1 is fixed as constraint. The constraint clearance (Fig. 2) is the same in two loading steps. The billet is TA15 alloy and whose flow behavior is from the work of Shen [23]. In FE modeling, the deformation is simplified as a plane strain problem and isothermal process. The von Mises yielding criteria, constant shear friction model, automatic remeshing, and local refined meshing techniques are employed. The geometry dimensions of FE model are shown in Fig. 2a. The billet height (H) and reduction amount are 30 and 12 mm, respectively. To study the effect of die parameters, the fillet radius (r) of three ribs varies from 3 to 9 mm. And the constraint clearance (c) ranges from 0.5 to 2.5 mm. As for the processing parameters, the deformation temperature is set as 950 °C. The loading speed and friction factor locate in the ranges of 0.1–0.9 mm/s and 0.1–0.5, respectively.

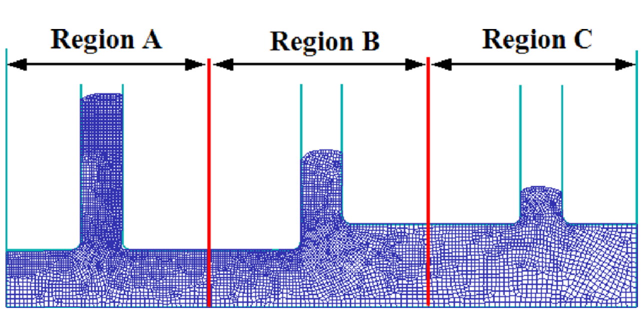

Fig. 3 Schematic of the regional division in the workpiece

2.2 Quantitative characterization of the deformation characteristics

Large inhomogeneous deformation may produce some macro-defects such as folding in the local loading forming of Ti-alloy component. Moreover, inhomogeneous deformation may lead to nonuniform microstructure because of the strong microstructure sensitivity of titanium alloy [5, 13]. Thus, it is critical to investigate the deformation inhomogeneity for improving the forming quality during local loading forming of Ti-alloy component. A previous developed user subroutine in DEFORM-2D [10, 13] was used to quantitatively analyze the material flow and uneven deformation in the transitional region. In the subroutine, the extent of uneven deformation is evaluated by an area-weighted inhomogeneity index as follows [13].

$$\varphi = \sum_{i=1}^{N} s_i \left(\overline{\varepsilon}_i - \overline{\varepsilon}_{ave}\right)^2 \Big/ \sum_{i=1}^{N} s_i \tag{1}$$

where s_i and $\overline{\varepsilon}_i$ are the area and effective strain of element i, respectively, $\overline{\varepsilon}_{ave}$ is the area-weighted average effective strain of all elements expressed by $\overline{\varepsilon}_{ave} = \sum_{i=1}^{N} s_i \overline{\varepsilon}_i / \sum_{i=1}^{N} s_i$. The area-

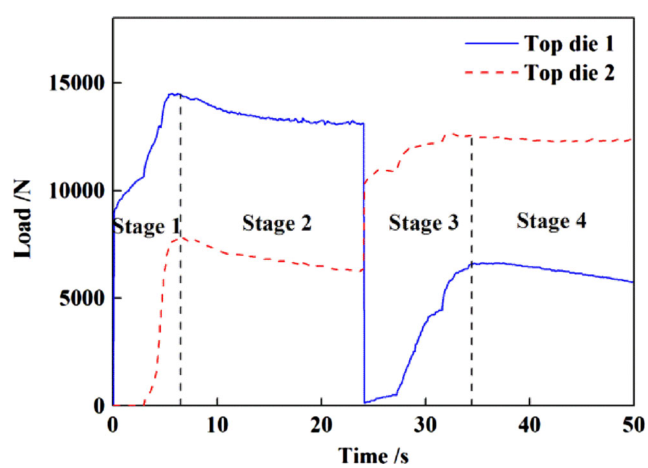

Fig. 4 Load-time curve in the local loading forming on double-action press

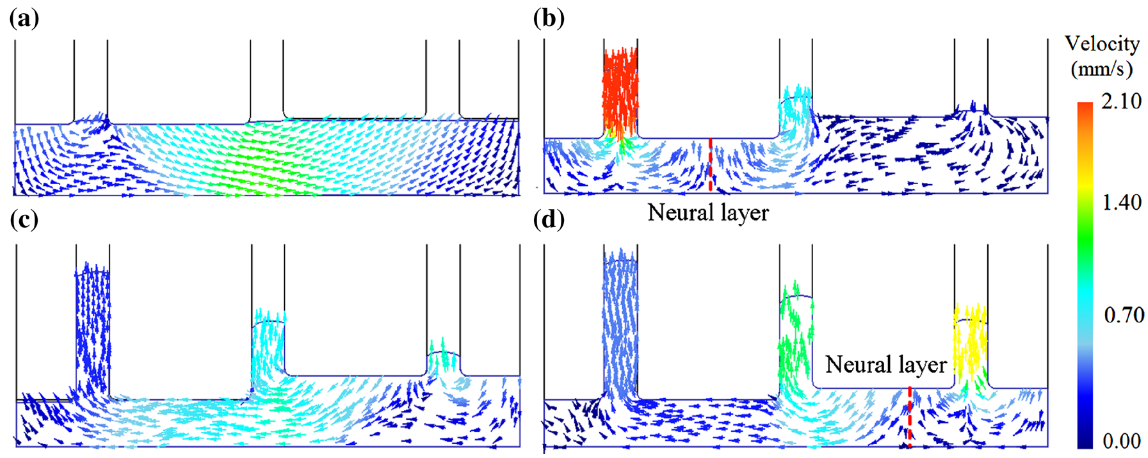

Fig. 5 The representative material flow patterns during local loading forming on the double-action press. **a** Stage 1, stroke = 0.8 mm. **b** Stage 2, stroke = 7.34 mm. **c** Stage 3, stroke = 2.38 mm. **d** Stage 4, stroke = 7.44 mm

weighted strain inhomogeneity index is applied to guarantee the comparability of inhomogeneity indexes among various regions and samples. This is because great differences exist on the number of elements and total area among different concerned regions. In addition, the element areas are inconsistent in FE simulation due to the uncertainty of element meshing. Therefore, the element area is considered in the inhomogeneity index (Eq. (1)), i.e., the area-weighted treatment is applied. Besides, the material quantity of any prescribed region can be calculated by summing up the area of each element in the corresponding region. In this work, the transitional region was divided into three subregions (Fig. 3), whose material quantities and deformation inhomogeneities were calculated. The deformation inhomogeneity of regions A, B, and C and the whole workpiece are noted as φ_A, φ_B, φ_C, and φ_T, respectively. The severity of cavum defect is expressed by its depth and noted as D.

3 Deformation characteristics of transitional region

In this section, the deformation characteristics (material flow, deformation inhomogeneity, and forming defect) of transitional region during local loading forming on double-action press are analyzed through a typical sample. The processing parameters of the typical sample analyzed here are as follows. The friction factor is 0.3, loading speed is 0.5 mm/s, constraint clearance is 1.5 mm, and the fillet of radius of three ribs are 3 mm. Moreover, these characteristics are compared with those local loading formed on single-action press in the previous works [10, 13, 14].

3.1 Analysis of material flow

As far as the material flow is concerned, the whole local loading process can be divided into four forming stages with two stages in each loading step according to the load-time curve (Fig. 4) and variation of velocity field. Figure 5 shows the

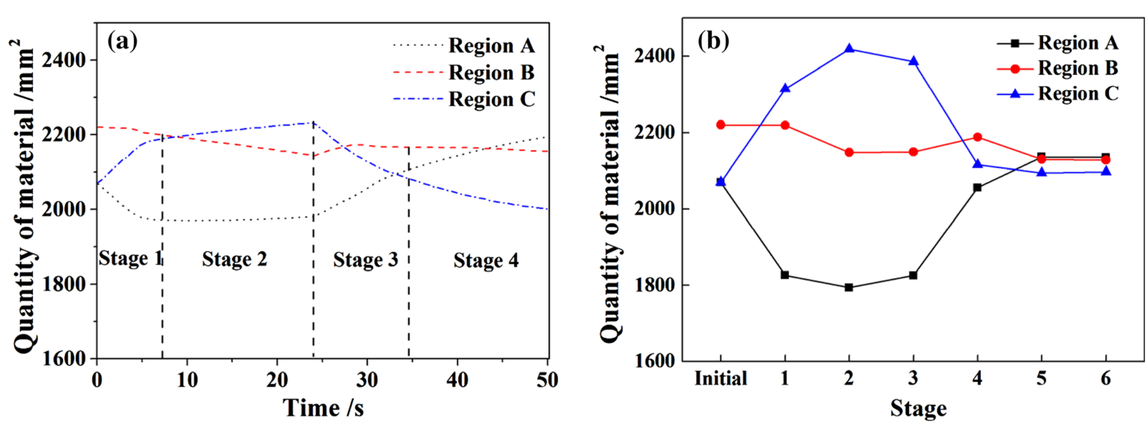

Fig. 6 The variation of material quantity of different sub-regions in transitional region during local loading forming process. **a** Double-action press. **b** Single-action press [10]

Table 1 The change degree of material quantity in each sub-region during forming process

	Region A	Region B	Region C
Double-action press	224.7 mm^2	76.4 mm^2	231.4 mm^2
Single-action press	341.7 mm^2	91.8 mm^2	347.9 mm^2

representative material flow pattern during each forming stage. For the stage 1, in first loading step, top die 1 presses the workpiece, while there exists a constraint clearance between top die 2 and workpiece. As the stroke increases, the material under top die 1 fill into the left rib and move right simultaneously because of the lower resistances under top die 2. When the clearance between top die 2 and workpiece disappears, stage 2 begins. In stage 2, the resistance under top die 2 increases so that the rightward flow of material is suppressed and a neural layer emerges between the left rib and middle rib (Fig. 5b). Stage 2 lasts to the end of first loading step. After the first loading step, the left rib and middle rib are filled to some extent, while the right rib is filled slightly. For the stage 3 in second loading step, top die 2 presses the workpiece. The material under top die 2 fill into the right and middle ribs and move left at the same time due to the constraint clearance under top die 1. When the clearance under top die 1 disappears, stage 4 begins. In this stage, the leftward flow of material is suppressed and a neural layer produces between the right rib and middle rib because of the increase of resistance under top die 1 (Fig. 5d).

Figure 6a shows variation of material quantity of different sub-regions in the transitional region during the local loading forming process. It can be found that the variation of material quantity also can be divided into four stages corresponding to those in Fig. 4. The quantity of material in region A decreases first in stage 1and changes little in stage 2. Then, it increases in both of stages 3 and 4, while the increasing rate in stage 3 is greater. The quantity of material in region B shows a descending trend basically in the whole process, but the decreasing amount is small. On the other side, the material quantity in region C increases first in stage 1 and nearly keeps steady in stage 2. Subsequently, it decreases in both of stage 3 and stage 4 with larger decreasing rate in stage 3.

The evolutions of material flow pattern and material quantities in different sub-regions indicate that the material in transitional region flow rightward first and then flow leftward in two loading steps respectively. This rule is basically the same as that in the local loading forming on single-action press [10]. However, there is a big difference on the change degree of material quantity in each sub-region during forming process, as given in Table 1. Here, the change degree means the difference value between the maximum and minimum material quantity during forming process, which can evaluate the extent of transverse material flow in transitional region. It can be found that the change degree on double-action press is greatly smaller than that on single-action press for each sub-region, especially for region A and region C. Previous studies [10, 14] found that there exists a strong positive correlation between the extent of transverse material flow and forming defects in transitional region during local loading forming. Thus, the forming quality on double-action press may be better than that on single-action press, which will be analyzed in detail in Section 3.3.

3.2 Analysis of deformation inhomogeneity

Figure 7a shows the changes of deformation inhomogeneities of different sub-regions during forming on double-action press. It can be found that they all increase gradually with the forming process but present different changing rates. The deformation inhomogeneity of Region A (φ_A) increases quickly in the first loading step but changes little in the second loading step. Conversely, the deformation inhomogeneity of Region C (φ_C) nearly keeps 0 in the first loading step, while

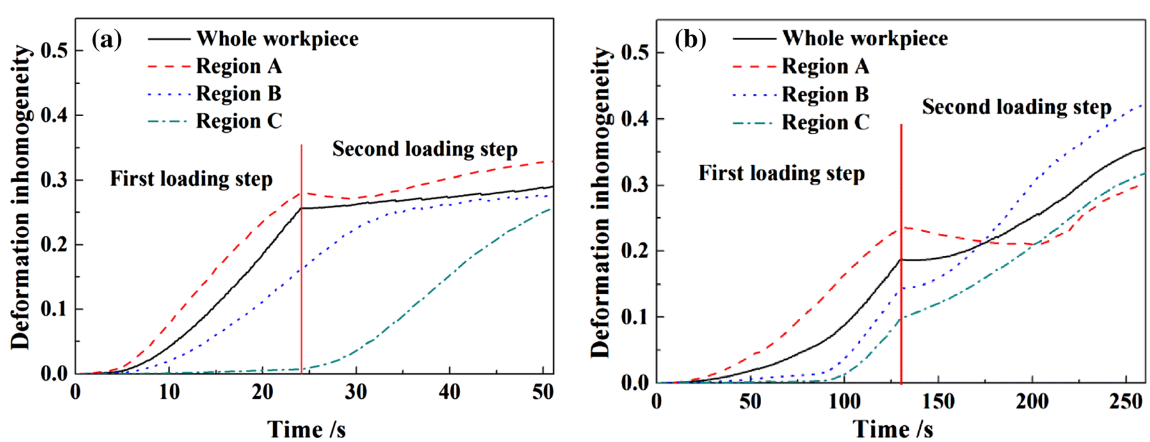

Fig. 7 The variation of deformation inhomogeneity during the local loading forming process. **a** Double-action press. **b** Single-action press [13]

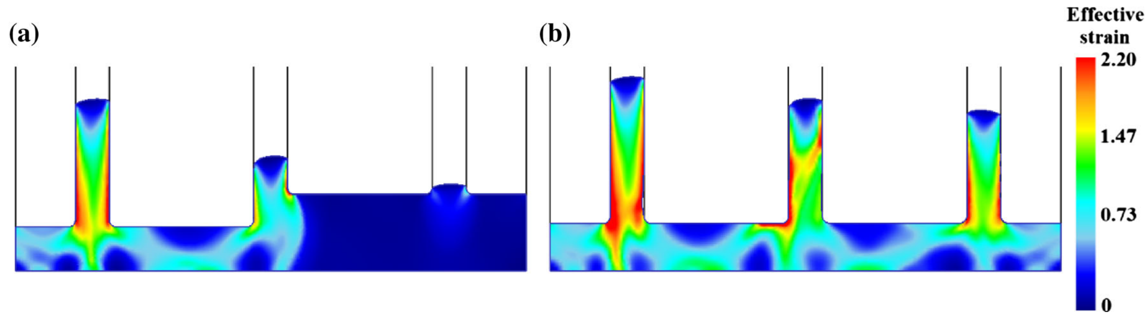

Fig. 8 The strain distribution during the local loading forming process on double-action press. **a** After the first loading step. **b** After the second loading step

increases rapidly in the second loading step. While, the increase extents of deformation inhomogeneity of Region B (φ_B) in two loading steps are very close. The variation trend of deformation inhomogeneity of whole workpiece (φ_T) are similar to that of region A but with smaller values. The above change rules in the first loading step are very similar to those on single-action press (Fig. 7b). In addition, they present the same order of deformation inhomogeneities of different regions: $\varphi_A > \varphi_T > \varphi_B > \varphi_C$. The corresponding strain distribution after first loading step is given in Fig. 8a. However, the change rules in the second loading step are different from those on single-action press, as shown in Fig. 7. Two forming types present different orders of deformation inhomogeneities of different regions after the second loading step. The order on double-action press after second loading step is $\varphi_A > \varphi_T > \varphi_B > \varphi_C$, which is the same as that after the first loading step. While the order on single-action press after second loading step is $\varphi_B > \varphi_T > \varphi_C > \varphi_A$. Moreover, the deformation inhomogeneity of each sub-region on double-action press is smaller than that on single-action press except for region A. Figure 8b shows the strain distribution of transitional region after the second loading step. It can be found that region A and region C present the similar strain distribution. Their deformation inhomogeneities are mainly caused by a symmetric strain concentration area at rib root, which is essentially related to the filling of rib. However, the strain distribution of region B is different from those of region A and region C. A slant strain concentration area generates at the middle rib, which leads to the deformation inhomogeneity of Region B.

3.3 Analysis of forming defect

Usually, the formation and evolution of forming defects during metal forging can be analyzed through the material flow [20, 21]. No forming defect was found in the workpiece after the first loading step (Fig. 9a); thus, the analysis of defects is focused on the second loading step. As mentioned above, at the beginning of second loading step, there exists a leftward material flow on the web due to the constraint clearance under top die 1 (Fig. 9b).Under the effect of leftward material flow, the material under left rib move left with its upward filling, which produces a cavum at the root of left rib, as shown in Fig. 9c. As the punch descends, more and more material flow into region A. The cavum under left rib would move up with the filling of ribs and become the cavum defect (Fig. 9d).

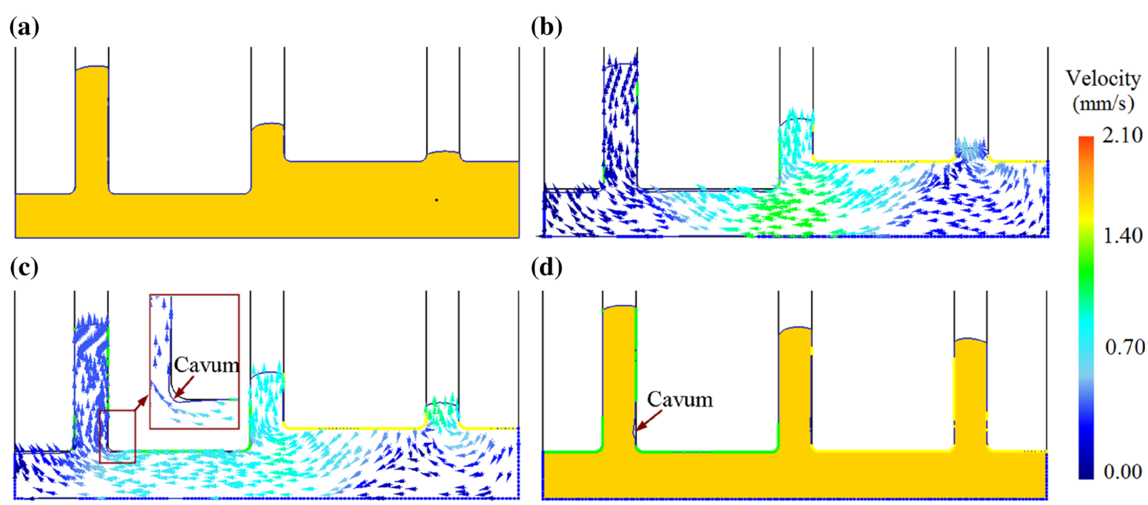

Fig. 9 The variation of velocity field distribution and defect during the local loading forming on double-action press. **a** The workpiece after first loading step. **b** Stroke = 0.70 mm. **c** Stroke = 2.68 mm. **d** Stroke = 11.84 mm

Table 2 Factors and levels of orthogonal experiment

Factors	Level 1	Level 2	Level 3
Factor A Fraction factor *m*	0.1	0.3	0.5
Factor B Loading speed *v* (mm/s)	0.1	0.5	0.9
Factor C Constraint clearance *c* (mm)	0.5	1.5	2.5
Factor D Radius of left rib r_1 (mm)	3	6	9
Factor E Radius of middle rib r_2 (mm)	3	6	9
Factor F Radius of right rib r_3 (mm)	3	6	9

It can be seen that the transverse material flow determines the formation of cavum defect in the forming on double-action press, which is the same as that on single-action press [10, 14]. But the forming quality on double-action press is better than that on single-action press. Only one cavum defect produces at left rib on double-action press, while two cavum defects and one folding defect generate on single-action press. This is because the extent of transeverse material flow in the forming on double-action press is greatly smaller than that on single-action press, as described in Section 3.1.

4 Influence of processing parameters on the deformation characteristics

4.1 Orthogonal experiment design

The orthogonal experiment design is a popular method to study the effect of influencing parameters on the results in various fields, since it can study the effects of many factors simultaneously in a single set of experiments with much fewer experiment units [24–26]. In this study, the effects of local loading parameters (friction factor, loading speed, and constraint clearance) and die parameters (fillet radius of three ribs) are concerned. An orthogonal array of seven factors and three levels, $OA_{18}(3^7)$ matrix, is used to assign the considered factors and levels, as shown in Table 2. On the other hand, the extent of transverse material flow, deformation inhomogeneities of region A and whole workpiece (φ_A and φ_T) and cavum depth (D) are the concerned results. As analyzed in Section 3.1, the material in transitional region flow rightward first and then flow leftward in two loading steps respectively during local loading forming. Moreover, it is reported that there exists a strong positive correlation between the extent of transverse material flow and forming defects in transitional region in the previous works [10, 14]. Therefore, the extent of transverse material flow (M_t) is taken as an important index in this work. It is defined as the sum of the change degrees of material quantity in three sub-regions during forming process. Here, the change degree means the difference value between

Table 3 Orthogonal experiment schemes and simulated results

No.	Factors						Forming results			
	m	*v* (mm/s)	*c* (mm)	r_1 (mm)	r_2 (mm)	r_3 (mm)	φ_A	φ_T	M_t (mm^2)	*D*(mm)
1	0.1	0.1	0.5	3	3	3	0.36	0.31	606.0	0.38
2	0.1	0.5	1.5	6	6	6	0.33	0.30	672.9	0.35
3	0.1	0.9	2.5	9	9	9	0.25	0.25	737.6	0.28
4	0.3	0.1	0.5	6	6	9	0.29	0.27	473.5	0.21
5	0.3	0.5	1.5	9	9	3	0.26	0.28	485.4	0.26
6	0.3	0.9	2.5	3	3	6	0.30	0.26	659.2	1.85
7	0.5	0.1	1.5	3	9	6	0.28	0.26	464.0	0.89
8	0.5	0.5	2.5	6	3	9	0.26	0.26	616.9	0.72
9	0.5	0.9	0.5	9	6	3	0.28	0.29	327.4	0.11
10	0.1	0.1	2.5	9	6	6	0.24	0.24	795.0	0.25
11	0.1	0.5	0.5	3	9	9	0.37	0.33	522.7	0.44
12	0.1	0.9	1.5	6	3	3	0.32	0.29	736.1	0.30
13	0.3	0.1	1.5	9	3	9	0.23	0.24	593.8	0.21
14	0.3	0.5	2.5	3	6	3	0.31	0.29	619.0	1.87
15	0.3	0.9	0.5	6	9	6	0.31	0.29	396.1	0.26
16	0.5	0.1	2.5	6	9	3	0.23	0.25	538.7	0.65
17	0.5	0.5	0.5	9	3	6	0.28	0.30	310.5	0.10
18	0.5	0.9	1.5	3	6	9	0.30	0.28	506.6	0.90

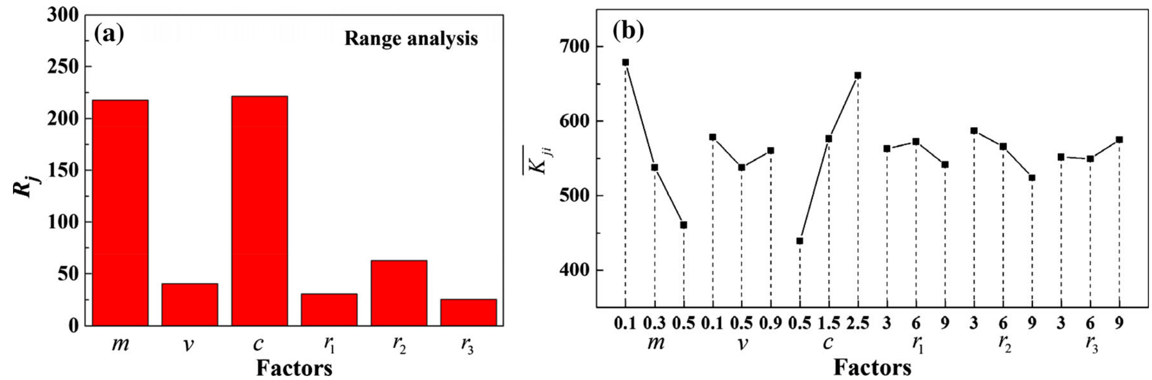

Fig. 10 Range analysis results on the extent of transverse material flow (M_t). **a** Range values of different factors. **b** The relationship between extent of material transfer and levels of different factors

the maximum and minimum material quantity during forming process. The detailed experiment scheme and calculated results are given in Table 3. According to the calculated results, the effect law and significance of factors on the results will be analyzed below.

4.2 Discussion

The range analysis is applied to study the effect significance and law of factors on the results. There are two important parameters need to be calculated in the range analysis, i.e., $\overline{K_{ji}}$ and R_j. $\overline{K_{ji}}$ is the average value of the indexes of all levels (i, $i = 1, 2, 3$) in each factor j at the same level i. R_j, the range value, is the range between the maximum and minimum value of $\overline{K_{ji}}$. A larger R_j means a greater significance of the factor R_j; thus, R_j can be used to evaluate the significance of factors.

Figure 10 shows the range analysis results on the extent of transverse material flow (M_t) during local loading forming. By comparing the range values of different factors (Fig. 10a), it can be found that m and c are two most significant factors for M_t. It can be seen from Fig. 10b that M_t decreases with the increase of m but increases with the increase of c. Larger friction factor would increase the resistance of material flow; thus, it is easy to understand that M_t decreases with the increase of m. As mentioned in Section 3.1, the transverse material flow is formed by the reason that the clearance between top die and workpiece in unloading region producing low constraint resistance. Therefore, increasing the clearance (c) would reduce the constraint resistance and increase the extent of transverse material flow.

The results of range analysis on the deformation inhomogeneity of region A (φ_A) are given in Fig. 11. It can be concluded from the range values of different factors (Fig. 11a) that r_1 is the most significant factor for φ_A. Next, m and c also influence φ_A to some extent. In addition, we can find that the above three factors present the same effect law on φ_A, i.e., increasing any factor could decrease φ_A. As described above, the deformation inhomogeneity of region A is mainly produced by the strain concentration area at the rib root. And this strain concentration area is related to the filling of rib. The increases of r_1, m, and c are all helpful to the material flow and filling of rib. This would relieve the degrees of grid distortion and strain concentration, thus decrease the deformation inhomogeneity.

Figure 12 gives the results of range analysis on the deformation inhomogeneity of whole workpiece (φ_T). It can be found that the range values in Fig. 12a are relatively smaller than those in Fig. 11a, which means that the sensitivity of φ_T to processing parameters is smaller than φ_A. Taken together,

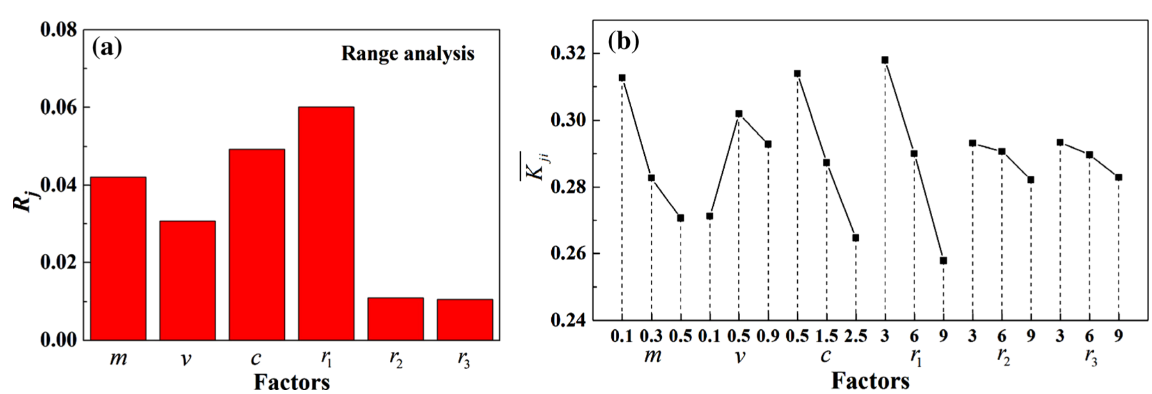

Fig. 11 Range analysis results on the deformation inhomogeneity of region A (φ_A). **a** Range values of different factors. **b** The relationship between deformation inhomogeneity and levels of different factors

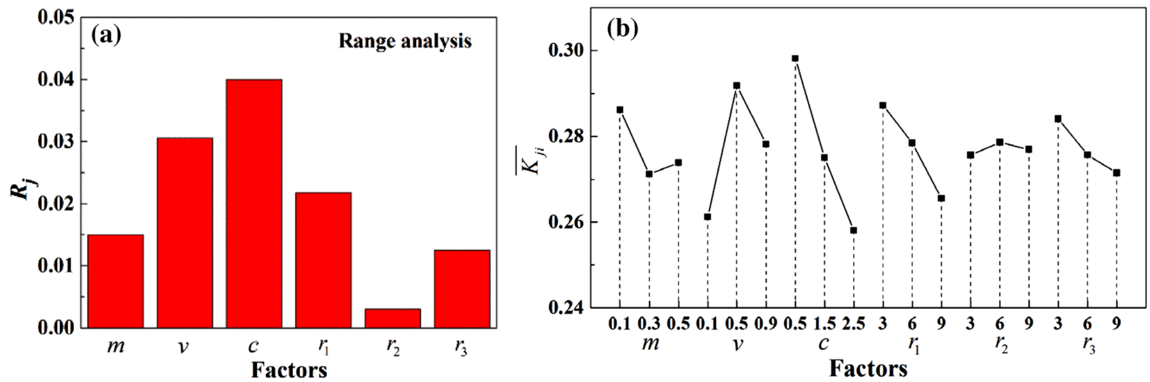

Fig. 12 Range analysis results on the deformation inhomogeneity of the whole workpiece(φ_T). **a** Range values of different factors. **b** The relationship between deformation inhomogeneity and levels of different factors

only c is a significant factor for φ_T. It can be seen from Fig. 12b that φ_T decreases with c.

Figure 13 shows the results of range analysis on the cavum depth (D). The range values in Fig. 13a indicate that r_1 and c are two significant factors for D. As demonstrated in Section 3.3, the cavum defect is generated due to the slight shift of rib root, which is essentially the result of leftward transverse flow of web material. Smaller c would decrease the extent of transverse material flow, thus suppress the cavum defect. While, greater r_1 would present smoother transition at the rib root and then suppress the cavum greatly. As a result, with the decrease of c or the increase of r_1, the cavum depth decreases gradually.

From the above analysis, it can be concluded that the constraint clearance is the most key factor for the local loading forming on double-action press. It plays significant effects on all of the material flow, deformation inhomogeneity and cavum defect. This is because the constraint clearance is the immediate cause of transverse material flow, which would then determine the deformation and evolution of cavum defect. Besides, the friction factor and radius of left rib are the second significant factors. Therefore, the constraint clearance, friction and radius of left rib need more concern in the design of processing parameters. The constraint clearance should take an appropriate moderate level. This is because decreasing the constraint clearance would suppress the extent of transverse material flow and cavum depth, while increase the deformation inhomogeneity. On the other hand, both of the friction factor and radius of left rib should take greater levels, which are helpful for decreasing the extent of transverse material flow, deformation inhomogeneity of region A, and the cavum depth.

5 Conclusions

In this paper, the material flow, deformation inhomogeneity, forming defect of transitional region, and their dependences on the processing parameters during local loading forming on double-action press were quantitatively analyzed. It can be concluded that:

(1) Due to the constraint clearance, the web material in transitional region flow rightward first and then flow leftward in two loading steps respectively, which is basically the same as that in the local loading forming on single-

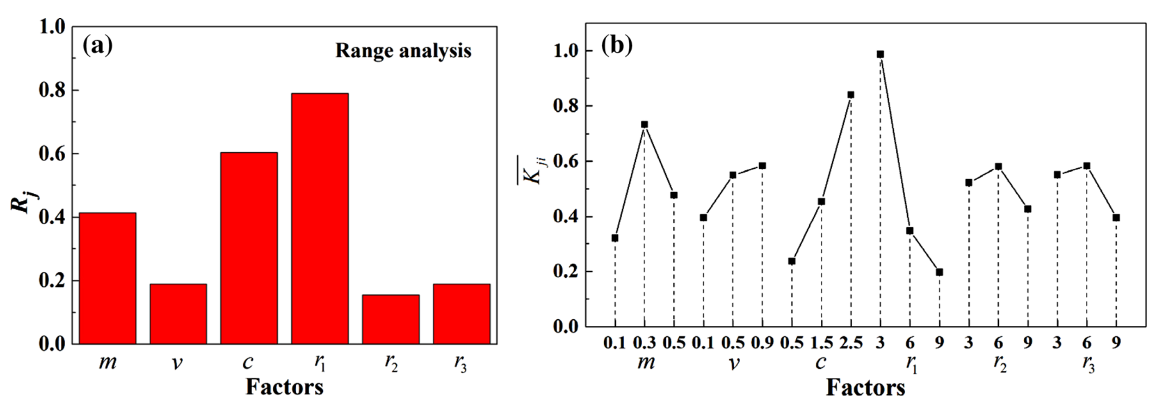

Fig. 13 Range analysis results on the cavum depth (D). **a** Range values of different factors. **b** The relationship between cavum depth and levels of different factors

action press. However, the extent of transverse material flow on double-action press is greatly smaller than that on single-action press.

(2) Different strain distributions were produced in various sub-regions of transitional region. Region A and region C present a symmetric strain concentration area at rib root, while region B presents a slant strain concentration area at the middle rib. The order of deformation inhomogeneities of different regions is Region A > whole workpiece > Region B > Region C.

(3) Only a cavum defect at left rib is produced by the transverse material flow during local loading on double-action press. This is better than that on single-action press with two cavum defects and one folding defect. Considering the forming quality, it is a better way to realize the local loading forming on double-action press than on single-action press.

(4) Constraint clearance is the most key factor for the local loading forming on double-action press. Decreasing the constraint clearance is benefit to suppress the transverse material flow and cavum defect, but the deformation inhomogeneity would increase to some extent. Besides, the friction factor and radius of left rib are the second significant factors. Increasing the friction factor and radius of left rib could suppress the transverse material flow and cavum depth, respectively.

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