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ARTICLE

# Distribution of Metal Flowing into Unloaded Area in the Local Loading Process of Titanium Alloy Rib-Web Component

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**Abstract:** For isothermal local loading process by means of partitioned die, the partition at a rib is generally adopted in order to reduce the disadvantageous influence of loading area on unloaded area. In the local loading process, some metal (flow-into metal) in loading area flow into unloaded area due to the local loading characteristic. The distribution of the metal flowing into unloaded area plays an important role in analyzing the forming process, controlling the metal flow, and improving the forming quality. The distribution of flow-into metal coming from loading area is mainly determined by the shape of the unloaded area and the geometric parameters near the die partitioning boundary. If the unloaded area is a formed area then some of the flow-into metal will fill the cavity of partitioning rib. A predicted model for the ratio of flow-into metal distributed to cavity of partitioning rib has been established by using partial least squares regression. The numerical simulation result indicates that the analysis on distribution of flow-into metal and the predicted model are reasonable.

**Key words:** rib-web component; local loading; partition at rib; numerical simulation; partial least squares regression

Isothermal local loading process has been used to form the large-scale integral rib-web component of titanium alloy because of the enormous forming force and the narrow processing windows of the alloy[1]. The isothermal local loading process is an isothermal forging under local loading way, which integrates the advantages of the isothermal forging and the local loading forming. The local loading method realized by dividing the upper or lower die into several parts is a simple and efficient way[2,3].

The large-scale rib-web components have not only the large geometric size and the complex-shaped structure but also an extreme size characteristic, and thus these bring the difficulties to analyze and study the forming process of the whole component. Exploring of the basic law of forming process can be carried out by considering deformation on planes of metal flow[4,5], and investigating the forming process of put forward and designed eigenstructure[6,7]. For large-scale rib-web component, the metal flow and cavity fill on representative cross sections can be quickly predicted by analytic method such as slab method (SM), and the initial range of forming parameters may be obtained based on analytic result, and then the forming process can be optimized in a small range by using 3D-FE simulation for the whole component. Zhang et al[8] developed a SM model to describe the metal flow and cavity fill in the local loading process of T-shaped component. The initial range of forming parameters may be provided based on the metal flow and the filling laws of T-shaped components local loading forming. However, during local loading process, some metal in loading area will flow into unloaded area due to local loading characteristic. The metal flowing from the loading area to the unloaded area is named flow-into metal. How to distribute the flow-into metal is one of the key problems urgently to be solved before using the SM model to analyze the local loading process of multi-ribs.

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For the certain material, the distribution of the flow-into metal is determined by the shape of unloaded area and the geometry parameters near die partitioning boundary (DPB), and the detailed ratio of the flow-into metal filling the partitioning rib cavity is determined by the geometry parameters. Thus, in the present work, the distribution of the metal flowing into unloaded area in the local loading process by partition at rib has been study, and the detailed ratio of the flow-into metal filling the partitioning rib cavity has been modeling by partial least squares(PLS) regression method. The numerical simulation result indicates that the analysis on the distribution of the flow-into metal and the PLS model are reasonable. The results of the present study provide a basis for the fast prediction of metal flow and cavity fill by using analytic method.

## 1 Research method

### 1.1 Description of eigenstructure and local loading process

Previous works[9,10] indicate that the influence of loading area on unloaded area is a short effect, which affects the region from the DPB to the first rib of unloaded area and the influence on the region beyond the first rib is little. Some of metal in the region from the DPB to the first rib of loading area will flow into unloaded area, and most of the flow-into metal is distributed over the region from the DPB to the first rib of unloaded area. Thus, in order to simplify the analysis and the experiment, the eigenstructure shown in Fig.1a is put forward and designed. The distances between two ribs, the rib heights and the rib widths of rib 1~3 are $a_{12}$, $a_{23}$, $h_1$, $h_2$, $h_3$, $b_1$, $b_2$, $b_3$ respectively.

The lower die is divided into two parts which are lower dies 1 and 2, and the die partitioning boundary is the center of rib 2, as shown in Fig.1b. During isothermal local loading process, the dies and the billet are heated to the same temperature, and only lower die 1 or 2 is loaded. The process has two local loading steps: in the first local loading step, lower die 1 is loaded whilst a constraint is applied to unloaded area by lower die 2; in the second local loading step, lower die 2 is loaded

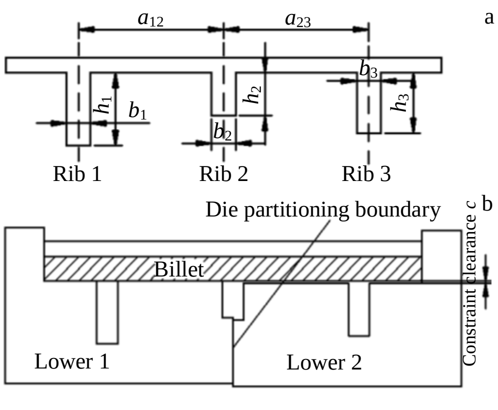


Fig.1 Eigenstructure and its local loading process: (a) geometry and (b) local loading process

and lower die 1 is fixed as a constraint; the constraint depends on the constraint clearance *c* between billet and unloaded die.

### 1.2 FE model of isothermal local loading

Under the FE soft environment of DEFORM, the FE model for the isothermal local loading process shown in Fig. 1b is developed based on plane strain. In the FE model, the thermal events are neglected due to the isothermal forming; the Von. Mises yielding criteria and the shear friction model are employed; local refined meshing and automatic remeshing techniques are used to improve computational efficiency and avoid mesh distortion; the material of the billet used in this work is Ti-6Al-4V, and its flow behaviors come form the material library of DEFORM; the forming temperature is 950 ℃; the shear friction factor is 0.3; the loading speed is 1 mm/s.

Through changing the geometric models of the billet and the dies according to the size of component shown in Fig.1a, different isothermal local loading processes can be carried out. The research in Ref. [11] indicated that the variable-thickness region of a billet should avoid setting at the position near the DPB. Thus, the billet with a uniform thickness is adopted, whose length and height are designed to guarantee that ribs 1 and 3 are filled. The FE model has been verified with rib height[8] and folding defect[11]. Thus, based on the validated FE model, the numerical simulation results in the present in this work can considered to be valid.

### 1.3 PLS regression method

PLS regression (PLSR) can analyze the data with strongly multi-collinear, small sample size, and numerous predictor variables, and also simultaneously model several response variables[12,13]. The literatures [12,13] presented the details about PLS regression method.

The predictor $\boldsymbol{X}$ and response variables $\boldsymbol{Y}$ are expressed as $\boldsymbol{X}=(\boldsymbol{x}_1,\boldsymbol{x}_2,\cdots,\boldsymbol{x}_p)_{n\times p}$ and $\boldsymbol{Y}=(\boldsymbol{y}_1,\boldsymbol{y}_2,\cdots,\boldsymbol{y}_q)_{n\times q}$ respectively. Using the PLS regression method the following regression equation Eq. (1) can be obtained. Usually, the ***X***- and ***Y***- variables are centered and scaled before PLSR analysis in order to make their distribution be fairly symmetrical. The importance of $\boldsymbol{x}_k$ for $y$ is given by $\mathrm{VIP}_k$ (variable importance for the projection). If all the $\mathrm{VIP}_k$ are equal to 1, then the importance of all ***X***-variables are the same; else if $\mathrm{VIP}_k>1$, then $\boldsymbol{x}_k$ is very important for modeling of ***Y***.

$$\boldsymbol{Y}=\boldsymbol{XB} \tag{1}$$

## 2 Results and Discussion

### 2.1 Analyzing distribution of flow-into metal

The volume of flow-into metal is determined by geometry parameters in the region from the DPB to the first rib (rib 1 or 2 in the first or second local loading step) of loading area, such as the thickness of a billet and the distance between DPB and the center of rib 1 or 2. The distribution of flow-into metal is determined by the shape of unloaded area and the geometry parameters near DPB.

In the first local loading step, the flow-into metal will fill the clearance between the billet and the unloaded die at first and then the cavity of rib 2 is filled because the shape in the unloaded area almost maintains the simple shape of the billet. In the second local loading step, some of flow-into metal fills the cavity of rib 2 and the other is distributed over the unloaded area due to nailing effect of the formed rib. Zhang et al [10] reported that about 50%~70% of flow-into metal fills the cavity of the partitioning rib. In general, most of flow-into metal which does not flow into cavity of rib 2 is distributed between the cavities of rib 1 and rib 2.

The exploring of the distribution of flow-into metal in the second local loading step is important for the fast analysis of the process. The volume of metal flowing into the cavity of rib 2 in the second local loading step is determined by the filling resistance in the cavity of rib 2 and the restricted effects of formed region. The filling resistance is determined by the filling depths of rib 2 after first ($h_s$) and second ($h_e$) local loading step, and the restricted effects are determined by tance $a_{12}$ and constraint clearance $c$ in the unloaded area. Volume ratio $y$ of metal flowing into the cavity of rib 2 is also influenced by the volume of the flow-into metal. Thus, in the second local loading step, volume ratio $y$ can be expressed by Eq. (2) according to above analysis.

$$y = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4 x_4 + a_5 x_5 \tag{2}$$

where $a_0 \sim a_5$ are the regression coefficients; $x_1 = c$; $x_2 = a_{12}/b_2$, $x_3 = a_{23}/b_2$, $x_4 = h_s/b_2$, $x_5 = h_e/b_2$.

### 2.2 PLS regression modeling

The orthogonal experiment design array $L_{27}(3^{13})$ is adopted to obtain sample data to establish the PLSR model of the volume ratio $y$. The levels of factors are determined according to relevant handbooks[14,15] and the local loading processing characteristics of one large-scale titanium alloy component with a thin web and a high rib. The orthogonal experiments are carried out by means of numerical simulation. If the cavity of rib 2 is filled completely after the first local loading step, then the experiment should be removed in this work. Thus, only 24 experiments are used in this work, and the response variable $y$ under different predictor variables $x$ are obtained according to numerical results, which are listed in Table 1.

The simple PLSR model is used in this work, in which there is only one response variable. One simple PLSR is carried out, and regression coefficients $a_0 \sim a_5$ can be obtained, and $y$ can be expressed by Eq. (3). The plot of the $X$-scores ($t_1/t_2$) and $T^2$ ellipse shows that the sample points are homogenous. The plot of $Y$-score $\boldsymbol{u}_1$ vs. $X$-score $\boldsymbol{t}_1$ indicates that the correlation coefficient between them is 0.93.

$$\begin{aligned} y = {} & 70.6962 - 13.9510x_1 - 1.6230x_2 - \\ & 0.0284x_3 - 6.1193x_4 + 10.3362x_5 \end{aligned} \tag{3}$$

However, the VIP of the $X$-variables, as shown in Fig.2, indicates that the $\mathrm{VIP}_3$ and $\mathrm{VIP}_4$ are about 0.5. It implies that the $x_3$ and $x_4$ may be not important for modeling of $\boldsymbol{Y}$. Fig.2 also illustrates the regression coefficients for the data after being centered and scaled. The absolute values of coefficients for $X$-variables can be ranged as following: $x_3 < x_4 < x_1 < x_2 < x_5$. It can be found that the absolute value of the coefficient of $x_3$ is very small, and thus the $x_3$ has little influence on the $y$, so the $x_3$ can be neglected. Generally, the $h_s$ is little in the local loading process of the multi-rib with a proper un-

**Table 1 Sample data for the volume ratio $y$**

| No. | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $y$/% |
|---|---|---|---|---|---|---|
| 1 | 0.75 | 2.00 | 2.000 | 0.421 | 1.000 | 67.766 |
| 2 | 0.75 | 4.00 | 4.000 | 0.480 | 2.000 | 73.565 |
| 3 | 0.75 | 6.00 | 9.000 | 0.173 | 3.000 | 78.910 |
| 4 | 1.00 | 6.00 | 7.875 | 0.186 | 2.000 | 66.320 |
| 5 | 1.00 | 6.00 | 10.500 | 0.055 | 3.000 | 76.757 |
| 6 | 1.00 | 4.00 | 10.500 | –0.009 | 1.000 | 60.415 |
| 7 | 1.50 | 6.00 | 15.000 | –0.025 | 3.000 | 69.166 |
| 8 | 1.50 | 9.00 | 15.000 | –0.112 | 1.000 | 45.067 |
| 9 | 1.50 | 4.00 | 10.000 | –0.042 | 2.000 | 69.061 |
| 10 | 1.00 | 10.50 | 4.500 | 1.152 | 2.000 | 46.029 |
| 11 | 1.00 | 15.75 | 6.000 | 1.855 | 2.742 | 48.690 |
| 12 | 1.00 | 5.25 | 6.000 | 0.092 | 1.000 | 54.193 |
| 13 | 1.50 | 10.500 | 10.50 | –0.077 | 1.826 | 50.158 |
| 14 | 1.50 | 5.250 | 10.50 | –0.062 | 1.000 | 51.329 |
| 15 | 1.50 | 7.875 | 7.00 | 0.007 | 2.000 | 57.906 |
| 16 | 0.75 | 7.000 | 10.00 | 0.005 | 1.919 | 70.046 |
| 17 | 0.75 | 10.500 | 22.50 | –0.072 | 3.000 | 71.929 |
| 18 | 1.50 | 15.000 | 6.00 | 0.653 | 2.530 | 51.844 |
| 19 | 1.50 | 5.000 | 6.00 | –0.044 | 1.000 | 50.187 |
| 20 | 1.50 | 10.000 | 4.00 | 0.089 | 1.982 | 51.585 |
| 21 | 0.75 | 15.000 | 15.75 | –0.076 | 3.000 | 67.309 |
| 22 | 1.00 | 10.000 | 11.25 | –0.043 | 1.643 | 58.747 |
| 23 | 1.00 | 15.000 | 15.00 | –0.047 | 1.686 | 51.873 |
| 24 | 1.00 | 11.250 | 15.00 | –0.082 | 1.000 | 49.963 |

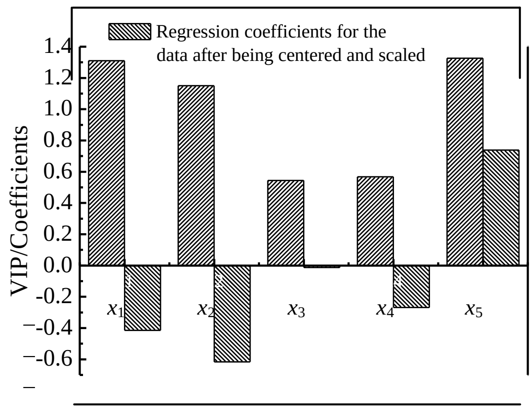


Fig.2 VIP of the $X$-variables and regression coefficients for PLSR model Eq.(3)

equal-thickness billet. The absolute value of the coefficient of $x_4$ is about 60% of that of $x_1$ and one third of that of $x_5$, which is also small. In order to simplify the PLSR model, the $x_4$ is also be neglected considering both of the $VIP_4$ and the coefficient of $x_4$, so the Eq. (2) can be simplified as Eq. (4).

$$y = a_0 + a_1 x_1 + a_2 x_2 + a_5 x_5 \tag{4}$$

One simple PLSR is carried out for the Eq. (4), and regression coefficients $a_0, a_1, a_2, a_5$ can be obtained, and $y$ can be expressed by Eq. (5). The plot of the $X$-scores ($t_1/t_2$) and $T^2$ ellipse shows that the sample points are homogenous. The plot of $Y$-score $\boldsymbol{u}_1$ vs. $X$-score $\boldsymbol{t}_1$ indicates that the correlation coefficient between them is 0.90. Fig.3 illustrates the VIP of the $X$-variables of the PLSR model Eq. (5) and the regression coefficients for the data after being centered and scaled. It indicates that three VIP are almost equal to 1 and the three coefficients are almost equal to corresponding coefficients in Fig.2. The volume ratio $y$ of metal flowing into the cavity of partitioning rib in the second loading step can be predicted by the PLSR model Eq. (5).

$$y = 70.3184 - 12.5083x_1 - 1.8182x_2 + 9.8023x_5 \tag{5}$$

### 2.3 Application of the model

The local loading characteristic caused by die partition has been studied, and the fast predicted models for a metal flow and a cavity fill have been established by SM[8]. Based on the SM models established in Ref. [8] and the analysis in Sections 2.1 and 2.2, the local loading process of multi-ribs as shown Fig.4a can be analyzed quickly, in which the designed rib height is adopted instead of $h_e$ in application of PLSR model Eq. (5).

During the process shown in Fig.4a, lower die 1 is loaded at first, and then lower die 2 is loaded, and constraint clearance $c$ =1 mm. The process is also analyzed by using finite element method (FEM). The shapes (predicted by FEM and SM) of a multi-ribs component after two local loading steps are shown in Fig.4b. It can be seen form Fig.4c that the shapes of the partitioning rib (rib 4) and the web between rib 3 and 4 predicted by SM in which the PLSR model Eq. (5) is used agree well with those predicted by FEM. The error of metal volume in the rib cavity between SM and FEM is less than 15%, but the CPU time consumed by FEM is about $2.30\times10^5$ times than that consumed by SM. The results indicate that the analysis about distribution of metal flowing into unloaded area and the PLSR model Eq. (5) are reasonable.

The above study and discussion are based on the Ti-6Al-4V which is a ($\alpha$+$\beta$) titanium alloy, so the PLSR model Eq. (5) can be used in the isothermal forming (at elevated temperature) process for this kind of titanium alloy. In China, another titanium alloy, TA15 (Ti-6Al-2Zr-1Mo-1V) titanium alloy which is a near-alpha titanium alloy is also widely used. For these two kinds of titanium alloy, the cavity filling behaviors in the isothermal forming (at elevated temperature) process are similar, as shown in Fig.5. Thus, the PLSR model Eq. (5) is also suitable for the TA15 titanium alloy.

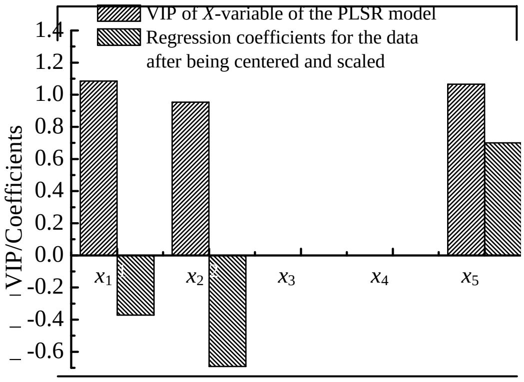


Fig.3 VIP of the $X$-variables and regression coefficients for PLSR model Eq.(5)

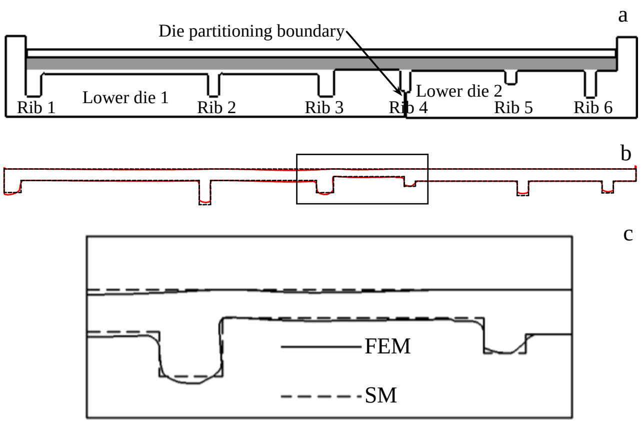


Fig.4 Local loading process of multi-ribs: (a) FE model, (b) shape of multi-ribs after two local loading steps, and (c) shape in enlarging area

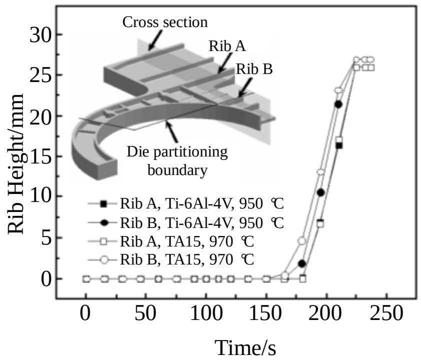


Fig.5 Rib heights on the cross section in the local loading process by using different materials (FEM result)

## 3 Conclusions

1) There exists some metal (flow-into metal) flowing from loading area into unloaded area due to local loading characteristic. The distribution of the flow-into metal is determined by

the shape of the unloaded area and the geometry parameters near DPB.

2) Under the partition at a rib, the flow-into metal will fill the constraint clearance of the unloaded die at first when the unloaded area is an unformed area; some of the flow-into metal fills the cavity of partitioning rib when the unloaded area is a formed area.

3) The prediction model about the volume ratio of the metal filling cavity of partitioning rib to the flow-into metal is modeling by PLS regression method.

4) The results in the present study are used in the analytic analysis for local loading process, and the analytic result agrees well with the numerical simulation result.

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# 钛合金筋板类构件局部加载成形中流向未加载区材料的分配

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**摘　要：**对于通过模具分区实现的等温局部加载成形，为了减少加载区对未加载区的不利影响，一般会采用筋上分区模式。由于局部加载特征，在成形过程中加载区部分材料会流向未加载区。流入未加载区材料的分配对成形过程分析、材料流动控制、成形质量改进都有着重要影响。从加载区流入为未加载区材料的分配主要由未加载区的形状和模具分区附近的几何参数所确定。若未加载区是已成形区，部分流向未加载区的材料充填分区筋型腔。应用偏最小二乘回归建立了流入分区筋型腔材料比率的预测模型。数值结果表明流向未加载区材料分配的分析和所建立的预测模型是合理的。

**关键词：**筋板类构件；局部加载；筋上分区；数值模拟；偏最小二乘回归

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