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NUMERICAL ANALYSIS FOR THREE-DIMENSIONAL BULK METAL FORMING PROCESSES WITH ARBITRARILY SHAPED DIES USING THE RIGID/VISCO-PLASTIC ELEMENT FREE GALERKIN METHOD

Ping Lu, Shengui Huang and Kaiyong Jiang

College of Mechanical Engineering and Automation, Huaqiao University, Xiamen 361021, China

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Abstract. The rigid/visco-plastic element free Galerkin method is applied to analyze three-dimensional bulk metal forming processes with arbitrarily shaped dies. Mesh approximation method is used to describe the mould cavity and an interface program for reading STL data in ASCII format is developed. Positions of contact nodes are modified in terms of shortest distance principle from contact nodes to triangle patches. The problem of “normal vector blind area” caused by drawing vertical line to triangle patches to search perpendicular point is solved. A meshless method numerical analysis procedure is developed, and simulation analysis steps and program flow are presented. The meshless analysis of the three-dimensional non-steady metal deformation processes with arbitrarily shaped dies is realized. The “cross-shaped” extrusion process is simulated by the procedure and the corresponding experiment is carried out. The effectiveness and validity of the proposed methods and numerical simulation program are evaluated by comparing numerical analysis results with the experimental results.

1. INTRODUCTION

Meshless method [1-3] is proposed recently as a new numerical simulation method. It requires no mesh generation and remeshing, and has advantage in dealing with large deformation problems. Many researchers have applied meshless method to solve metal forming problems [4-6]. These research contributions drive the development for meshless method numerical simulation technology in analyzing the metal forming process. But those research highlight the attention on the application of meshless method in simulating two-dimensional metal forming process, and analysis examples studied in analyzing three-dimensional problems belong to relatively simple forming processes and both geometry shapes of dies and material flowing are less complicated. However, in practical production both material flowing and die geometrical shapes are extremely complicated. Therefore, further study is required for using meshless method to simulate three-dimensional metal forming process with arbitrarily-shaped dies.

This paper applies rigid/visco-plastic element free Galerkin method [7] to analyze three-dimensional bulk metal forming processes. A meshless method numerical analysis procedure is developed. In order to improve the generality and automation of the analysis program, the related key simulation techniques for analyzing three-dimensional bulk metal forming process with arbitrarily-shaped dies are studied. Technology for describing the geometrical information of dies is studied. A great interest is focused on the technique for modifying contact nodes. In order to validate the accuracy and reliability of

Corresponding author: Ping Lu, e-mail: pinglu@hqu.edu.cn

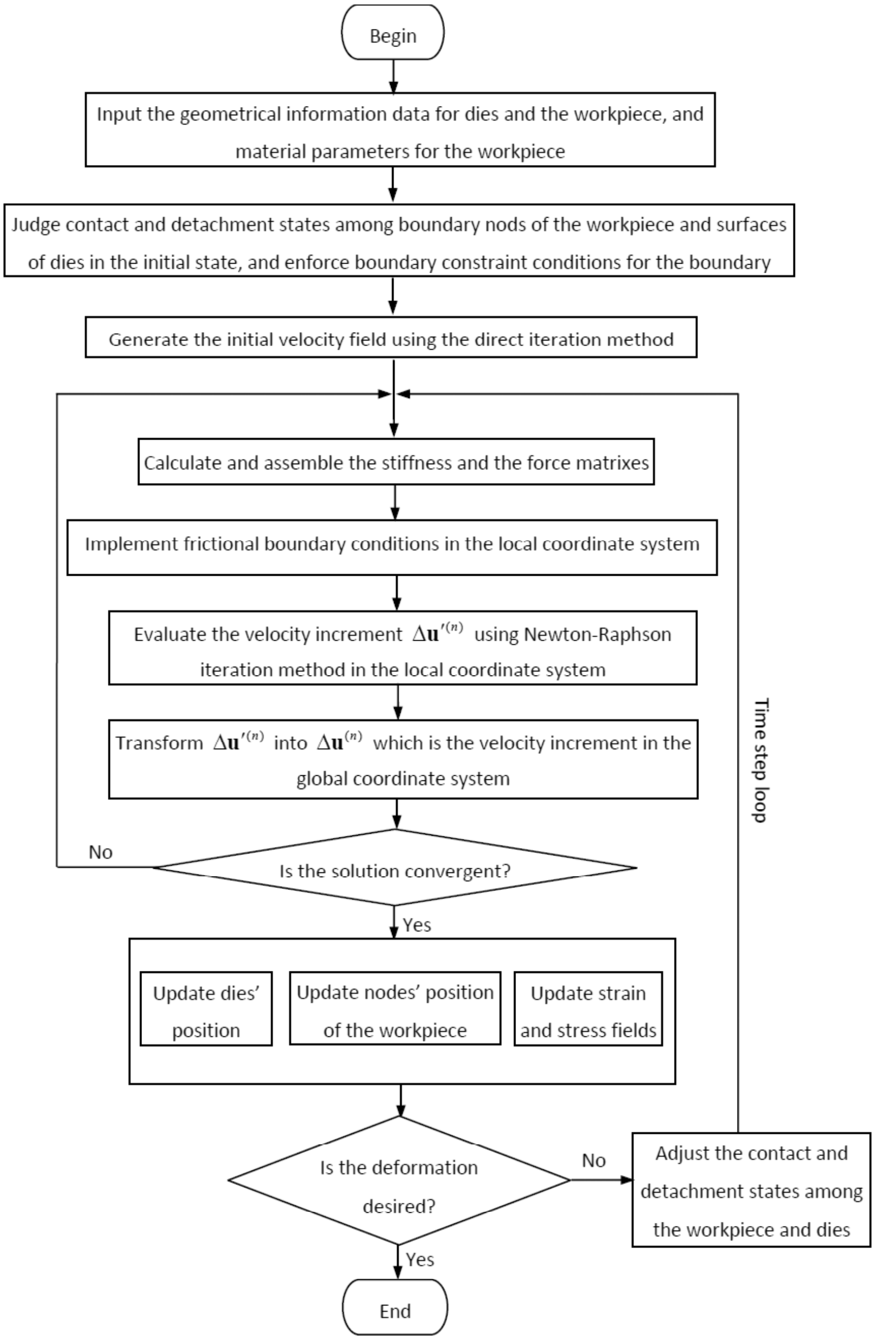

Fig. 1. The flowchart of rigid/visco-plastic element free Galerkin method numerical simulation for three-dimensional bulk metal forming processes.

the numerical simulation program, an unsteady "cross-shaped" extrusion process is analyzed by using the program and the corresponding experiment is carried out.

2. PROGRAM FLOW OF THE RIGID/VISCO-PLASTIC ELEMENT FREE GALERKIN METHOD

Based on the studies of rigid/visco-plastic element free Galerkin method, a program for simulating three-dimensional bulk metal forming processes with arbitrarily shaped dies is developed. The flow chart of the simulation procedure is shown in Fig. 1.

3. TECHNOLOGY FOR DESCRIBING THE GEOMETRICAL INFORMATION OF DIES

In order to simulate arbitrary shaped three-dimensional metal forming processes, the general and simple method should be adopted to describe die

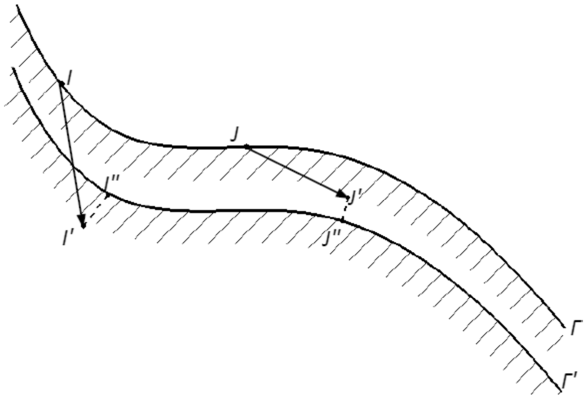

Fig. 2. The phenomena that contacted nodes separate from the die surface.

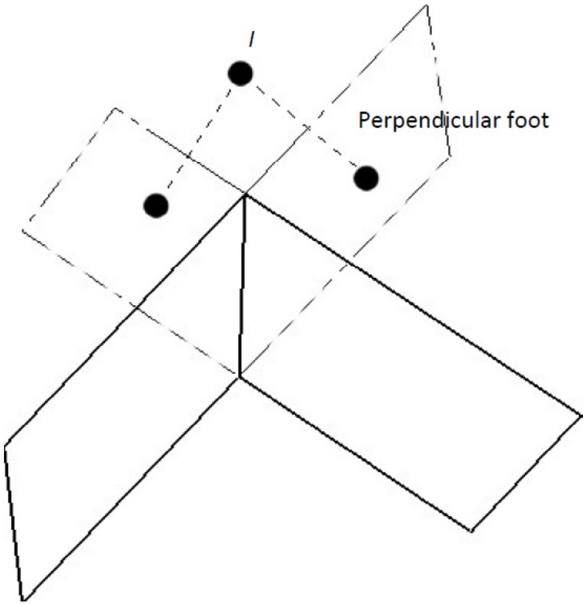

Fig. 3. The schematic diagram of “normal vector blind area”.

cavity surfaces. The main methods include analytic method, parametric surface method, and mesh approximation method. Mesh approximation description method uses a set of continuous discrete triangular or quadrangular patches to represent die cavity surfaces, and can almost describe all types of spatial surfaces. So it is employed to describe die cavity surfaces in the paper.

The information of die cavity surfaces is obtained through STL data with ASCII format exported by commercial CAD/CAM graphic software. The data format of an ASCII STL file includes all triangular patches' information, and every triangular patch's information consists of a normal vector and three vertices' coordinates.

Because one vertex connects with three triangles at least, so the coordinates for each vertex are saved repeatedly three times at least. Thus, there is a large number of redundant data in the STL file obtained by commercial CAD/CAM software. And if the original STL file is used directly, it consumes more memory of the computer, as well as reduces the computational efficiency. Therefore, the paper establishes the topology connection among triangular patches and all vertices, and generates the new STL file. Concretely, dynamic array is used to represent triangular patches in the procedure, and data members of a dynamic array variable are composed of a normal vector and three vertices' number rather than vertices' coordinates.

4. REPOSITIONING OF THE CONTACT NODES

It can be seen from Fig. 1 that dies' position and nodes' position of the workpiece should be updated,

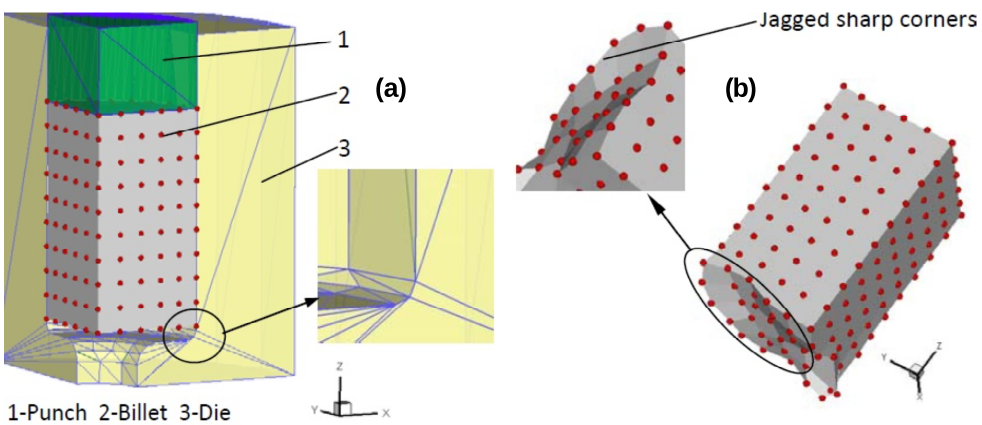

Fig. 4. The incorrect simulation results caused by “normal vector blind area”. (a) - Forward extrusion; (b) - The shape of the workpiece when the stroke is 4 mm.

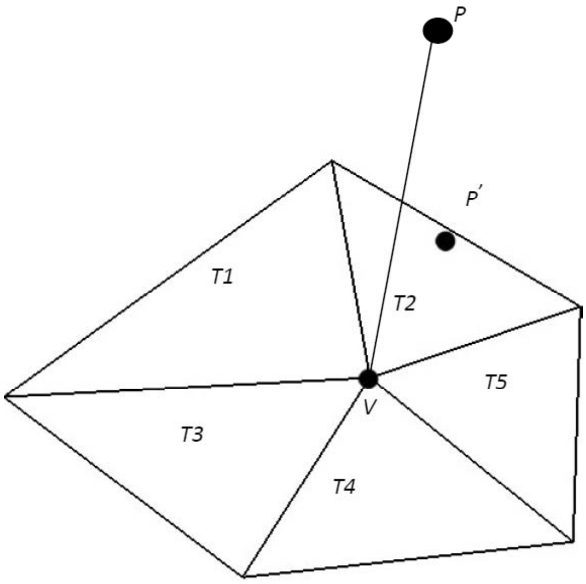

Fig. 5. The schematic diagram for adjusting the contact node.

and boundary contact nodes of the workpiece should still be on dies' surfaces after the convergent velocity field is obtained in one time step. Because the rigid/visco-plastic element free Galerkin method is an incremental deformation method and boundary contact nodes move along tangent directions of dies' surfaces rather than the surfaces in each time step. So the contact nodes will penetrate through dies' surfaces and enter the interior of the dies or depart from dies' surfaces. As shown in Fig. 2, Γ and Γ' are die's surfaces before and after updating position, *I* and *J* are two contact nodes, after updating position *I* and *J* locate at *I'* and *J'* respectively. It can be seen from the figure, *I* embeds within die and *J* separates from Γ' after updating position. This phenomenon is completely inconsistent with the actual deformation process. Hence, the position of boundary contact nodes should be adjusted.

Based on the principles that normal distance has minimum value, the contact node can be repositioned at the perpendicular foot by drawing a line perpendicular to die's surface through the contact node and seeking the perpendicular foot. As shown in Fig. 2, nodes *I'* and *J'* are modified at *I"* and *J"* respectively by employing this approach. This adjustment method is realized by procedure easily, so it is widely used in metal forming simulations.

But the adjustment method introduced above often yields unreasonable results in analyzing three-dimensional problems. This is because the mesh approximation method is used to describe die cavity surfaces. Discrete triangular patches do not necessarily connect smoothly, and that result in the appearance of "normal vector blind area". Fig. 3 shows this problem. It can be seen, node *I* is in the "normal vector blind area", and the perpendicular foot can not be found on triangular patches when drawing vertical line to triangular patches through *I*. If contact nodes locate at "normal vector blind area", they can't be adjusted correctly using the above method, and the simulation results are incorrect.

Fig. 4a shows a forward extrusion example, taking into account the symmetry of this example, 1/4 model shown in the figure is analyzed. Fig. 4b shows the shape of the workpiece when the stroke is 4 mm. As seen in Fig. 4a, there are "normal vector blind areas" in fillet transition regions of the die. Because some boundary contact nodes are in these regions after updating their positions. So perpendicular foots calculated by the method mentioned above are not on triangular patches when the bound-

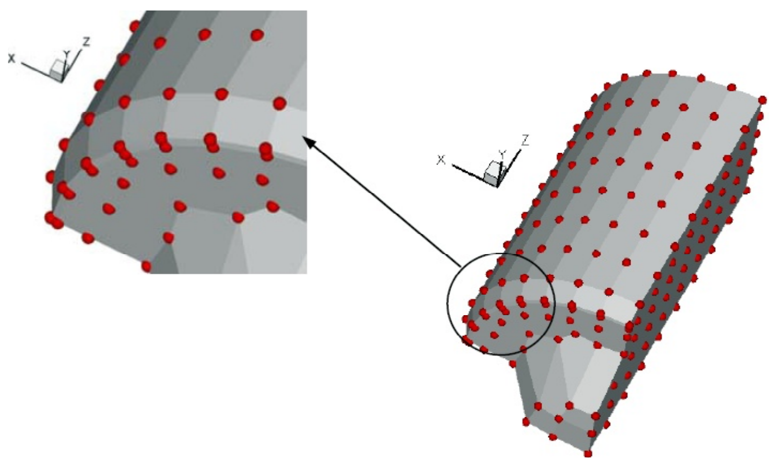

Fig. 6. The shape of extrusion part after modifying positions of the contact points used the method presented in the paper when the stroke is 6 mm.

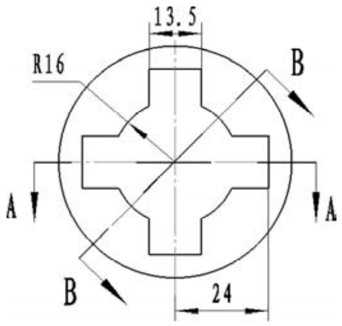

Fig. 7. The section shape and dimensions of the extrudate.

ary contact nodes are adjusted. It can be seen from Fig. 4b false simulation results are yielded, that is the nodes which are in the bottom of the billet and contact with die cavity surfaces embed within die, and jagged sharp corners are formed.

For solving the above problem, a simple approach is presented. The contact node is repositioned not under the law of minimum normal distance, but in terms of minimum distance to seek a point that is on triangle patches and has the shortest distance to the contact node. Node's location may be revised within the triangle, or on any one side of the triangle, or at triangle vertices. This approach avoids the phenomenon that perpendicular point cannot be found correctly by drawing a line perpendicular to die's surface patches through the contact node, and solves problems caused by "normal vector blind areas" successfully. In order to improve computational efficiency, the vertex which has the shortest distance to the contact node is found out firstly. As shown in Fig. 5, *P* is the contact node, *V* is the vertex which has the short distance to *P*. Then triangles which have this vertex should be found out. As seen in Fig. 5 *T1~T5* are the triangles. And finally the contact node is repositioned at these triangles which contain the vertex by the method proposed in the paper. As shown in Fig. 5, *P* is repositioned at *P'*.

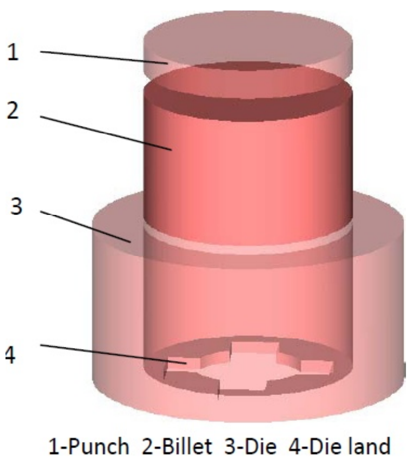

Fig. 8. The schematic diagram of extruding process.

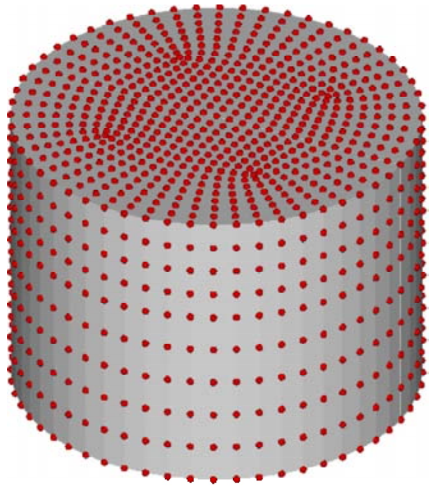

Fig. 9. The initially discretized model.

Fig. 6 shows the shape of extrusion part after modifying positions of the contact points used the method presented in the paper when the stroke is 6 mm. It is obviously that workpiece surface is smooth, and the contact nodes of the workpiece attach the die cavity well.

5. NUMERICAL EXAMPLE—THE "CROSS-SHAPED" EXTRUSION PROCESS

Fig. 7 shows the section shape and dimensions of the extrudate, A-A and B-B are two special cross-sections. Fig. 8 is the schematic diagram of the extruding process.

The initial size of the billet is ∅60 mm×44 mm, the velocity of the punch is 10 mm/s, the extrusion ratio is 3, the frictional factor among dies and billet is selected 0.15, the material is AA-6061 aluminum alloy, the material flow stress is

$$\bar{\sigma} = 70\dot{\bar{\varepsilon}}^{0.183}\ \text{MPa}. \tag{1}$$

During the meshless simulation, the billet is discretized with 6170 nodes as shown in Fig. 9. And Fig. 10 shows the shape of the extrudate when the displacement is 5.11 mm

In the extrusion process experiment, the metal flowing feature is investigated by using vision plasticity method. Firstly, the cylindrical billet is split into two parts along the axis, and mesh lines are drawn on the cross-section of one part, and then two parts are bonded together with strong adhesives.

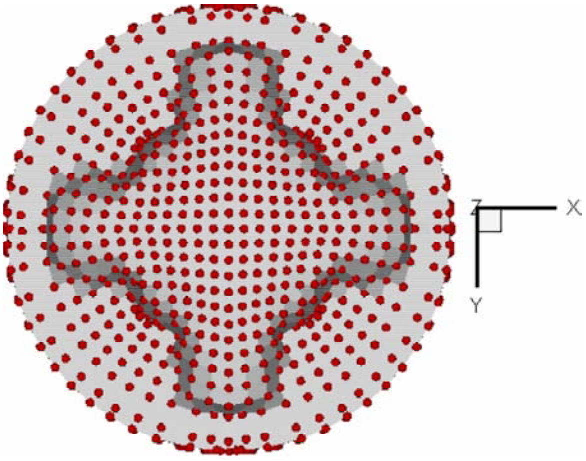

Fig. 10. The shape of the extrudate when the displacement is 5.11 mm.

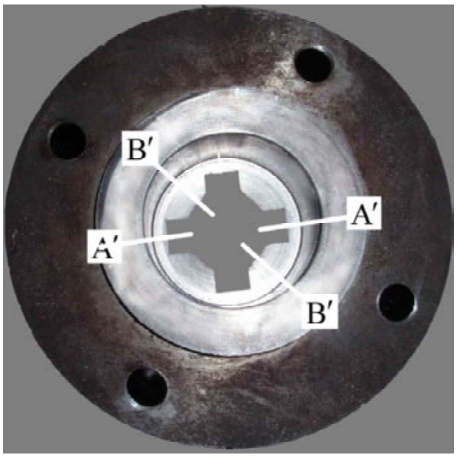

Fig. 11. Lines A’-A’ and B’-B’ signed on the die.

Meanwhile, lines A’-A’ and B’-B’ are painted on the die as shown in Fig. 11. Finally, the adhesive surface of the billet is aligned to A’-A’ and B’-B’, respectively. When a certain reduction is achieved, the metal flowing trends can be observed by stopping extruding and taking out the extrudate.

Figs. 12a and 12b describe velocity vector distributions on A-A and B-B cross-sections respectively obtained by element free Galerkin method when the displacement is 5.11 mm. From Fig. 12, it can be observed that the metal in middle zones of the workpiece has the highest speed, and the metal

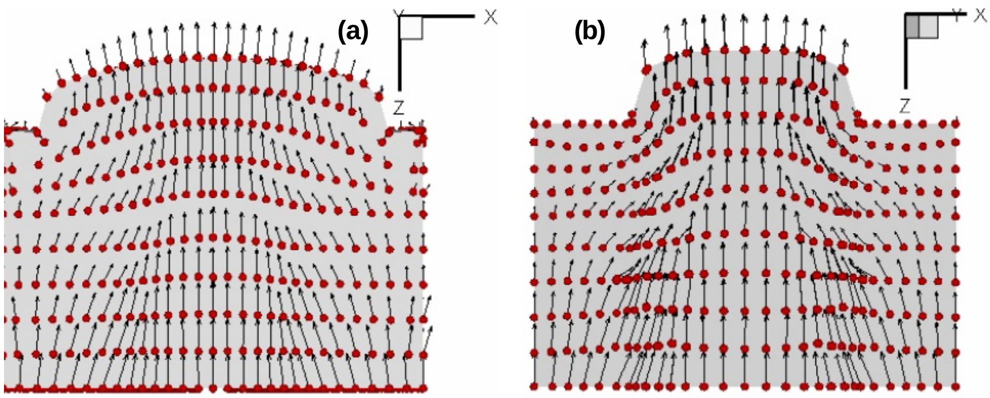

Fig. 12. Velocity vector distributions on cross-sections obtained by element free Galerkin method when the displacement is 5.11 mm. (a) A-A cross-section, (b) B-B cross-section.

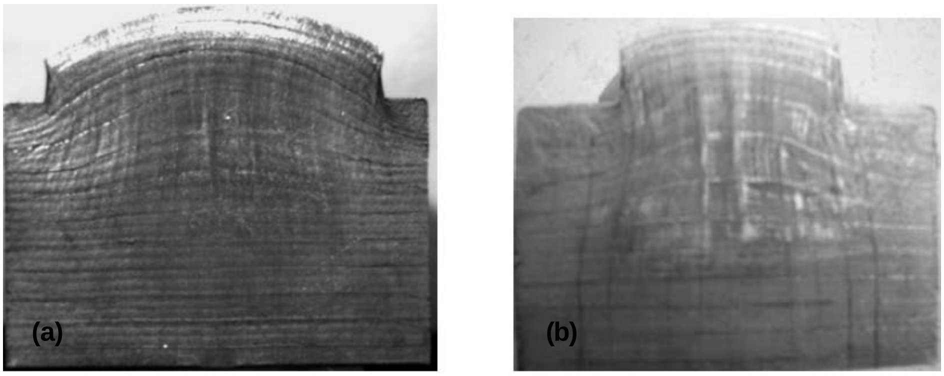

Fig. 13. Grids on cross-sections obtained by experiment when the displacement is 5.11 mm. (a) A-A cross-section, (b) B-B cross-section.

in edge areas flows slowly. Velocity decreases gradually from the middle areas to the periphery. That is because the effect of frictional resistance is concentrated on the boundary of the workpiece, and the metal in middle zones is affected little by frictional force. Therefore, this velocity distribution make boundary metals near the exit of extrusion die display a parabolic shape in the horizontal direction. What's more, the velocity of metal in the shoulder regions on both sides of the extrusion die is almost zero, so these regions are usually called the dead regions.

Figs. 13a and 13b show the grids on A-A and B-B cross-sections respectively gained by experiment when the displacement is 5.11 mm. It can be seen that the middle regions of the extrudate near the exit of extrusion die is protuberant, and horizontal lines of the grids display parabolic shapes. In addition, there are dead regions in the shoulder regions on both sides of the extrusion die.

Comparing Fig. 12 and Fig. 13, it can be found that velocity fields simulated by element free Galerkin method are in good agreement with metal flowing trends obtained by experiment.

6. CONCLUSIONS

Based on the studies of rigid/visco-plastic element free Galerkin method, an analysis program for simulating three-dimensional bulk metal forming processes with arbitrarily shaped dies is developed. Related key technologies are studied. STL file is employed to describe die cavity surfaces. The new STL file is established according the topology connection among triangular patches and all vertices, and the new STL file reduces memories of the computer and improves the computational efficiency. The approach for adjusting contact nodes is presented. Contact nodes are repositioned in terms of shortest distance principle from the contact node to triangle patches. Concrete steps of the approach are introduces. And problems caused by “normal blind are solved. The “cross-shaped” extrusion process is analyzed. The numerical results such as the shape of the extrudate and velocity vector distributions are obtained. Metal flowing regularity gained by the numerical procedure is in good agreement with the result obtained by experiment. The numerical example analysis demonstrate that the procedure is capable of simulating three-dimensional unsteady bulk metal forming processes with severe deformation and arbitrarily shaped dies.

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