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EFFECT OF PROCESS PARAMETERS ON THE END-FACE QUALITY OF CROSS-WEDGE ROLLING (CWR) SHAFT FROM TITANIUM ALLOY Ti6Al4V

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In order to verify the formability of CWR of titanium alloy Ti6Al4V, and to study effect of parameters on the end-face quality of CWR shafts from titanium alloy Ti6Al4V. The forming process was simulated with the DEFORM-3D software． The results show that the concavity increase with the increase of length and the diameter of billet; they decrease with the increase of spreading angle; they increase firstly and then decrease with the increase of area reduction; they decrease firstly and then increase slowly with the increase of forming angle. Also the order of the influence degree of the five parameters in descending order is: diameter of billet, length of billet, area reduction, spreading angle and forming angle. And the simulation results were verified by experiments.

Key words: titanium alloy Ti6Al4V, cross-wedge rolling, shaft, process parameters, concavity

INTRODUCTION

Titanium alloys are applied in aircraft, automotive, chemical, medical engineering industries as well as in many other areas, because of its high strength-to-weight ratio, elevated corrosion resistance, and ability to withstand high temperatures [1]. However, Titanium alloy is hard to be machined, because of its small deformation coefficient, small elastic modulus, and the active chemical properties [2]. The accuracy of forging method is lower than cross-wedge rolling, and the production continuity is worse than that of cross-wedge rolling.

Cross-wedge rolling is an advanced forming technology of shaft parts with high efficiency, energy saving and material saving. It is considered to be the best process for near-net forming shaft parts and has been widely used [3]. However, the concavity of shaft that processed by cross-wedge rolling causes the material utilization rate less than 85%. In order to further improve the material utilization rate, many researches have been done by scholars and experts. Z. H. Ma et al. analyzed the cross-wedge rolling shaft parts of 45 steel by ANSYS finite element software, and obtained the influence of process parameters on the size of the concavity [4]. J. Wei et al. analyzed the influence of forming angle, spreading angle, area reduction, and the length of the billet on the end-face quality of the 42CrMo steel during closed-open wedge rolling [5].

Although a lot of researches has been done on the end concavity of the wedge cross-rolling shaft for steel metal, the study on the wedge cross-rolling of titanium alloys is still in its infancy. In this paper, through the simulation and experimental verification, the effect of process parameters on the quality of the titanium alloy Ti6Al4V shaft end-face, which processed by cross-wedge rolling was studied.

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Establishment of cross-wedge rolling finite element model (FEM)

A rigid and plastic model of cross-wedge rolling was established by DEFORM-3D finite element software for numerical simulation, as shown in Figure 1. The guide plates and rolls were considered as rigid bodies. In order to improve the efficiency of simulation, due to the symmetrical feature of the billet and tools, only half of the FE model was created. The billet was divided into 50 000 tetrahedral element meshes. Moreover, billet material before forming was heated in its whole volume to the temperature 950 °C, yet tools temperature during simulation was constant and equal 20 °C. The diameter of the roller is 630 mm, and the speed of dies is 10 r/min. The material of billet is widely used titanium alloy Ti6Al4V.

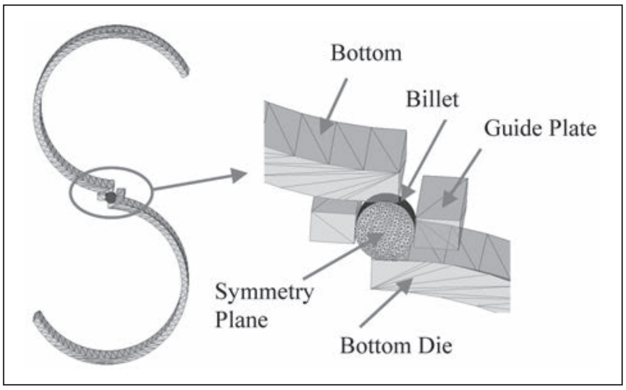

Figure 1 FEM for CWR simulation

ANALYSIS OF CONCAVITY FORMING MECHANISM AND DETERMINATION OF CONCAVITY SIZE

Analysis of concavity forming mechanism

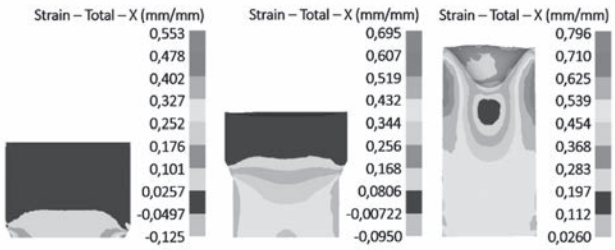

Figure 2 Axial strain field of the workpiece on the middle longitudinal section

The axial strain ε_x in the forming area of the workpiece is uneven tensile strain, as showed in the axial strain distribution in Figure 2. The workpiece surface is in contact with the dies. Under the extrusion of the dies, the axial strain in workpiece surface is larger and the axial strain in the core of workpiece is smaller. Therefore, in the cross-wedge rolling process, the displacement of metal in the workpiece surface is greater than that in the workpiece core. In the forming zoon, the uneven axial deformation of the surface and the core of workpiece increases until it enters the sizingzoon, which eventually generates concavities at the end of the shaft.

Determination of concavity size

In this paper, depth H was used to define the size of the concavity. 25 points are selected on the outermost side of the workpiece, as shown in Figure 3(b), and the average value of the axial coordinate $\frac{1}{25}\sum_{i=1}^{25} S_i$ was considered as the outermost coordinate value. The offset distance of the center point is generally less than 0,2 mm after rolling. Therefore, the center point of the cross-section of the workpiece was selected, which surrounded by 24 uniformly distributed points on the two circles of 0,1mm and 0,2 mm radius. The minimum value of the axial coordinate of the 25 points was taken as the bottom coordinates of the concavity as shown in Figure 3(a). The formula for the depth of the concavity is as follows:

$$\mathrm{H} = \frac{1}{25}\sum_{i=1}^{25} S_i - \{\min\} S_j$$

In this formula, H is the depth of the concavity; S_i is the outermost coordinates; {min} S_j is the minimum value of the axial coordinate of the 25 points.

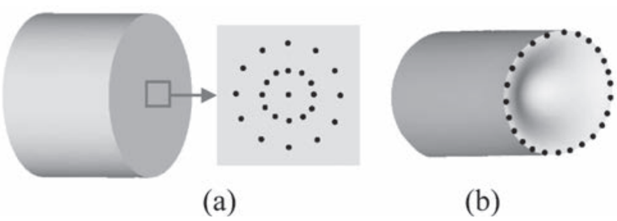

Figure 3 The position of the center 25 points (a) and the outermost 25 points (b)

SELECTION OF PROCESS PARAMETERS AND ANALYSIS OF SIMULATION RESULTS

Selection of process parameters

The parameters of dies (forming angle α, spreading angle β and area reduction φ) and the parameters of the billet (diameter of billet and length of billet) were both considered and adopted in the simulation. 25 groups of five conditions and five levels were used for simulation, as shown in Table 1.

Table 1 **Process parameters for simulation**

Forming angle α/°	Spreading angle β/°	Area reduction φ/%	Diameter of billet D/mm	Length of billet L/mm
20/23/26/29/32	7	50	40	60
26	5/6/7/8/9	50	40	60
26	7	30/40/5/60/70	40	60
26	7	50	34/37/4/43/46	60
26	7	50	40	40/50/6/70/80

ANALYSIS OF SIMULATION RESULTS

The influence of forming angle on the depth of concavity

The depth of the concavity decreases firstly and then increases slightly as the forming angle α increases, as shown in Figure 4. As the forming angle increases, the contact surface between the dies and the workpiece becomes narrower, the plastic deformation zone becomes deeper, the difference of axial strain between the surface and the core becomes smaller, and thus the concavity becomes smaller. When the forming angle reaches 29°, the concavity reaches the minimum value, but with the increase of forming angle, the concavity also increases slightly. This is because the forming angle is too large and the axial force component during rolling is also greater, which resulting in an increase of the concavity.

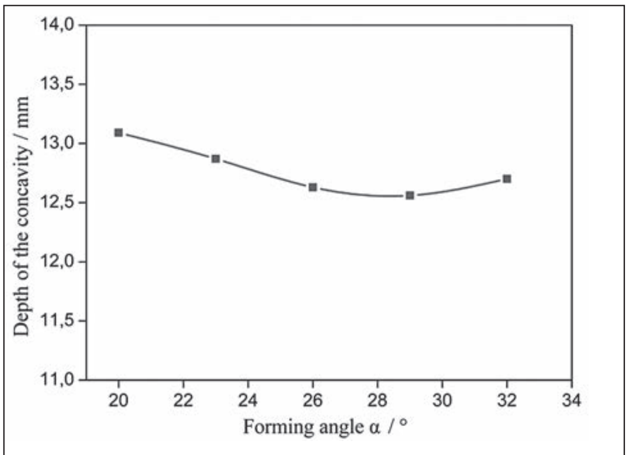

Figure 4 Relationship between the forming angle and the depth of the concavity

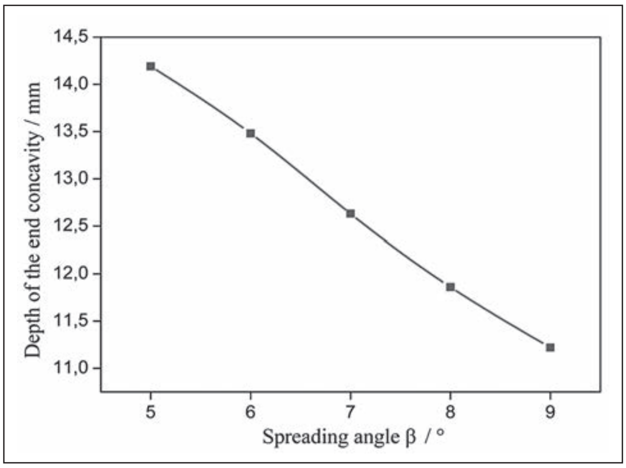

Figure 5 Relationship between the spreading angle and the depth of the concavity

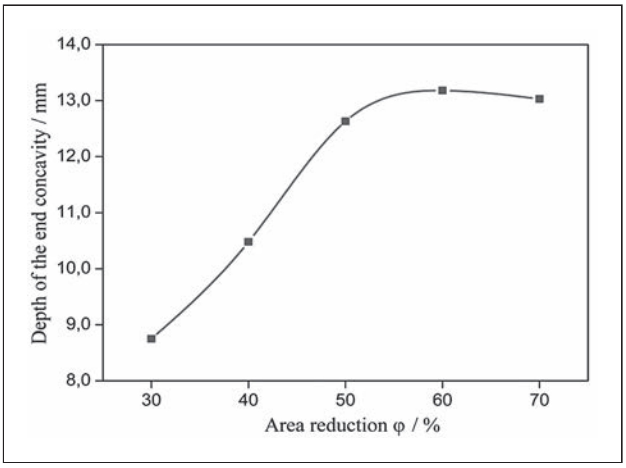

Figure 6 Relationship between the area reduction and the depth of the concavity

The influence of spreading angle on the depth of concavity

The depth of the concavity decreases nearly linearly as the spreading angle increases, as shown in Figure 5. Because as the spreading angle increases, the instantaneous contact area between the workpiece and the dies increases, and the axial rolling force is weakened. The axial flow of the metal becomes difficult, and the uneven of the axial deformation between surface and the core of workpiece is reduced, and thus the depth of the concavity is reduced.

The influence of area reduction spreading angle on the depth of concavity

The depth of the concavity increases firstly and then decreases slightly with the increase of the area reduction, as shown in Figure 6. Because the area reduction is greater, the length of rolling is longer, and the amount of metal axial flow is greater, which resulting in increased uneven deformation of the workpiece surface and core. When the area reduction exceeds 60 %, the depth of the concavity no longer increases, because the closer the rollers are to the center of the workpiece, the smaller the difference between the flows rate of the core metal and the surface metal.

The influence of billet diameter and billet length on the depth of concavity

As shown in Figure 7, 8, the depth of concavity increases with the increase of the billet diameter and billet length. Both the diameter of billet and the length of the billet have a great influence on the depth of the concavity. The main reason is that with the increase of the diameter of the billet, the flow of the metal in the core is more restricted, and the difference between the flow rate of the metal in the core and the surface is continuously increased; as the length of the rolling increases, the amount of uneven deformed metal accumulates is greater, the depth of concavity is greater.

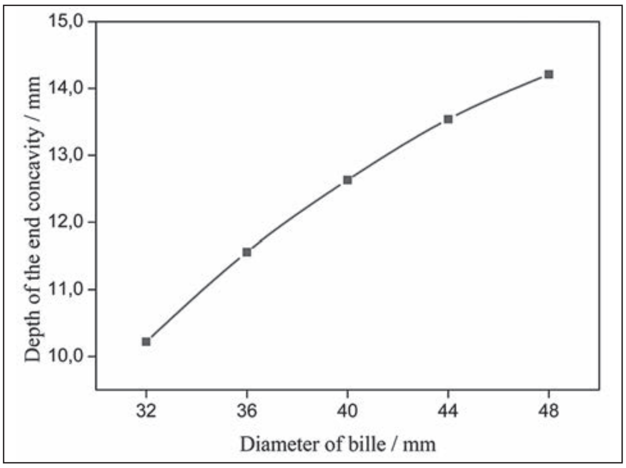

Figure 7 Relationship between diameter of billet and the depth of the concavity

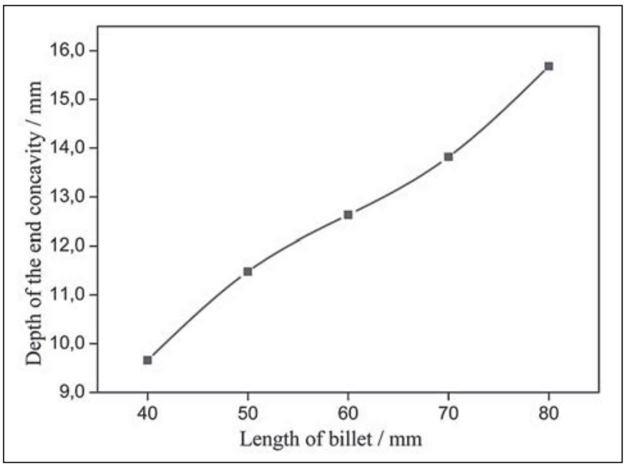

Figure 8 Relationship between length of billet and the depth of the concavity

THE ORDER OF THE INFLUENCING FACTORS

In order to study the order of various process parameters on the concavity, the dimensionless influence factor λ and the influence coefficient η were used in this paper and defined as: $\lambda_i = X_i/X_0$, $\eta_i = Y_i/Y_0$. In this formula, X_i is the value of the influencing factor; X_0 is the initial value of the influencing factor, Y_i is the depth of

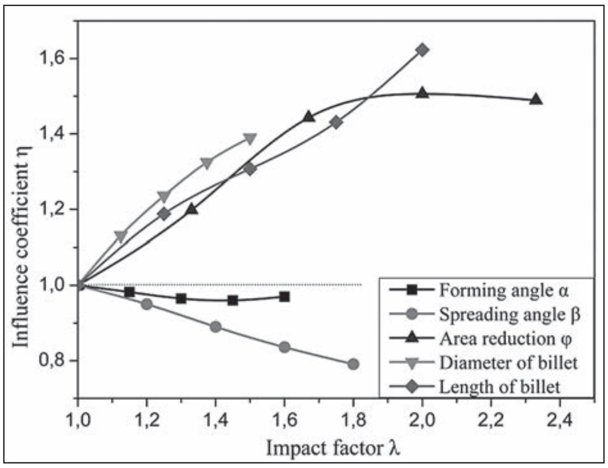

Figure 9 Influence degree of each factor on the depth of the concavity

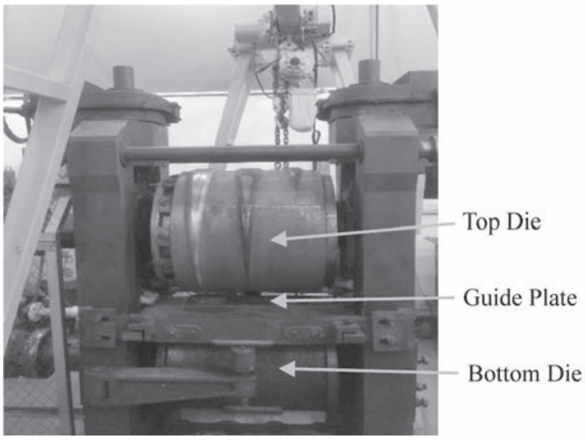

Figure 10 Experimental H630 mill

concavity, Y_0 is the initial value of the concavity. As shown in Figure 9, the greater the curvature of the curve, the greater the influence of this factor on the concavity. The order of the influence of the five parameters in descending order is: diameter of billet, length of billet, area reduction, spreading angle and forming angle.

CWR EXPERIMENT

The CWR experiments were carried out on the H630 rolling mill in the CWR laboratory of Ningbo University China. The rolling mill is shown in Figure 10. Taking into account the price of titanium alloy Ti6Al4V and the dies that have been made, the spreading angles $\beta_1 = 7°$, $\beta_2 = 8°$, and $\beta_3 = 9°$ were selected. Three groups of experiments were performed as shown in Figure 11. The depth of concavity in experiments and simulations compared as shown in Figure 12, the error is within 4 %, and the simulation is basically consistent with the experimental results.

CONCLUSION

(1) The formability of titanium alloy Ti6Al4V was verified by FE simulation and CWR experiment.

(2) The depth of concavity decreases with the increases of the spreading angle, increases with the increases of billet diameter and billet length; decreases firstly then increases with the increases of forming angle, and increases firstly and then decreases slightly with the increases of the area reduction.

(3) The order of the influence degree of the five parameters in descending order is: diameter of billet, length of billet, area reduction, spreading angle and forming angle.

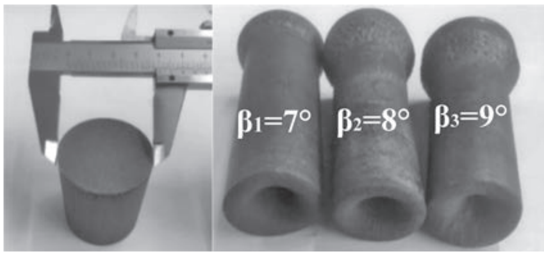

Figure 11 Billet and workpiece

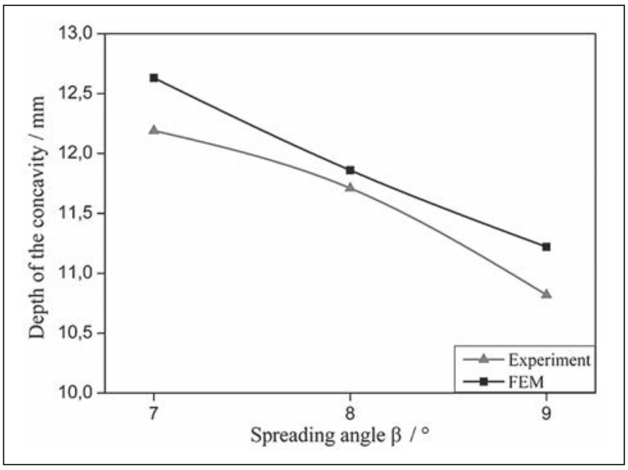

Figure 12 Results of experiments and simulations

Acknowledgements

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Note: The responsible translator for the English language is Q. Q. Yan, Ningbo, China