Optimization of Process Parameters for Three-roll Skew Rolling Based on Design of Experiment(DOE）

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1. Abstract
Titanium alloy with high strength, corrosion resistance, heat resistance and many other advantages,has widely applications in aviation industry and the military-industrial complex.Three-roll rolling is one of mature methods in current production of titanium alloy bars.In this paper, we take the titanium alloy bars TC 4 as the model and adapt DEFORM-3D finite element software to simulate the three-roll skew rolling process. By this means the feasibility of titanium alloy bar used in three-roll skew rolling and the deformation mechanisms are analyzed. Additionally, experiment design method is applied to determine the critical process parameters impacting the forming quality of three-roll skew rolling. Range analysis and variance analysis methods show that the influencing parameters of average distance of swirl marks in decreasing sequence are as follows: deflection angle, initial temperature of rolled piece, angular velocity of rolled piece, and the optimal parameter combination are as follows: deflection angle = 8, initial temperature = 900°C, angular velocity = 10 rad/s.
2. Keywords: Titanium alloy bar, three-roll cross rolling, numerical simulation, orthogonal experiment

3. Introduction
Titanium alloy material has low density, high melting point, high specific strength, heat resistance, corrosion resistance, small linear expansion coefficient, as well as good bio-compatibility, and because of its meet the strict requirements for the materials, such as the aviation industry can work normally under high temperature, corrosive environment, so in the aerospace, Marine transportation, automobile manufacturing, chemical industry, metallurgy and other industries plays an important role[1-2]. In recent years, China's aviation, aerospace, power and the rapid development of ocean engineering, all kinds of titanium products demand is growing, especially in the aircraft industry proportion is the largest, the application of titanium alloy in large passenger aircraft airbus A380 dosage of titanium alloy to 45 tons/frame, total weight of 10%; The same amount of titanium alloy material Boeing reached 15%. In the development of fighter jets, the requirement to have higher mobility, the fuselage as light as possible, the titanium alloy can better satisfy the use requirement.American F22 fighter, accounted for 39% of body weight, titanium alloy with titanium structure with 36 tons, two engines titanium 5 tons[3-4]. Titanium alloy in aviation air also measures the development level of high and low dosage, the applications of titanium alloy to aviation industry in China started late, aviation parts on the proportion of titanium alloy dosage still exists a certain gap compared with abroad.For example,in the batch production of titanium in the aircraft engine usage is not high, and Europe and the United States in some developed countries have the titanium dosage proportion on the engine has reached more than 30% [5-7]. Because of the expensive titanium alloy, in order to make full use of the titanium alloy bars, the application of three-roll skew rolling mill rolling into small diameter rod, effectively improve the material utilization rate. In addition, the three of three roll mill roll on bar uniform compressive stress, is more advantageous to the plastic deformation of metals.

4. The finite element model three-roll skew rolling

4.1. The determination of process parameters
Through a lot of three-roll skew rolling finite element simulation, combining with the actual production to determine a set of process parameters affecting the quality of skew rolling forming as shown in table 1.

Tab.1 Parameters of rolling process

Rolling temperature /°C	Roll angular velocity /rad/s	Deflection Angle /°	Tilt Angle /°
1000	10	8	5

4.2. Material model

Rolled piece material chosen as of TC4 titanium alloy, the plastic body. Material properties including material yield limit, ultimate strength, and the flow stress - strain relationship and so on, its deformation temperature at 800 ~ 800 °C, strain rate in 0.01 ~ 20 s^{-1} .TC4 material properties are shown in table 2.

Tab.2 Material property

Material parameters	Density (kg/m^3)	Elasticity modulus(Gpa)	Poisson’s ratio	yield stress (Mpa)	shear modulus (Gpa)
rolling meta	4400	100	0.34	919	44

4.3. Three-roll skew rolling finite element modeling

According to three in the three-roll skew rolling mill roll space position relations, roll the geometry size of three-roll skew rolling titanium alloy rod finite element model is established, in order to coordinate the z axis as the direction of the rolling line, three roll around the z axis direction of 120 ° evenly distributed, roll line and the rolling line intersection, each roll around the axis of rotation, contact each other, rolled piece from the bite into the roll end, under the effect of rolling friction was into three roll pass, as the bar shaft forward, its diameter decreases continuously. Three-roll skew rolling in the process of the finite element model is established, Due to the complexity of three roll location in space coordinates, to accurately set the deflection Angle and tilt Angle, two important parameters to ensure the smooth progress of rolling.

In actual production, the three-roll skew rolling mill space geometric relation of deformation zone, and the metal flow conditions are relatively complex.The following assumptions: (1) bar as a plastic body, only plastic deformation; (2) roll as a rigid body, the rigid-plastic finite element model. Because of the hot rolling is a large deformation process therefore the friction between the roller and the rolled piece can be set to the shear friction. Bar front circular conical design, convenient its bite.As shown in Figure 1.

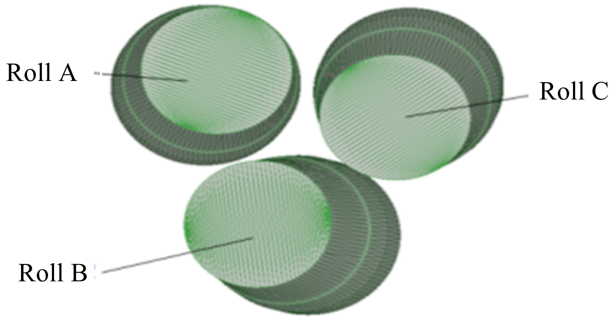
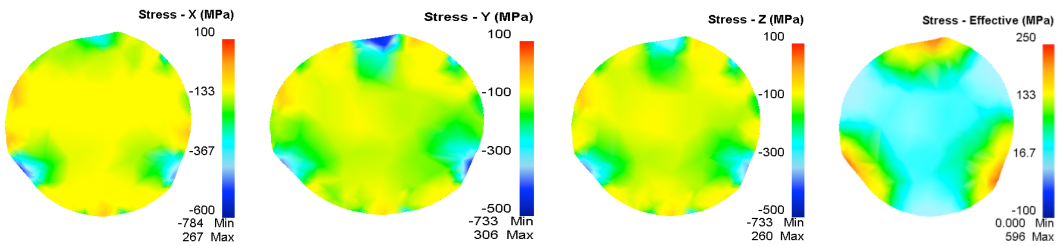


Fig.1 The finite element model of three-roll skew rolling

5.Titanium alloy rod three-roll skew rolling forming law



(a) Transverse stress σ_x (b) Longitudinal stress σ_y (c) Axial stress σ_z (d) Equivalent stress $\overline{\sigma}$

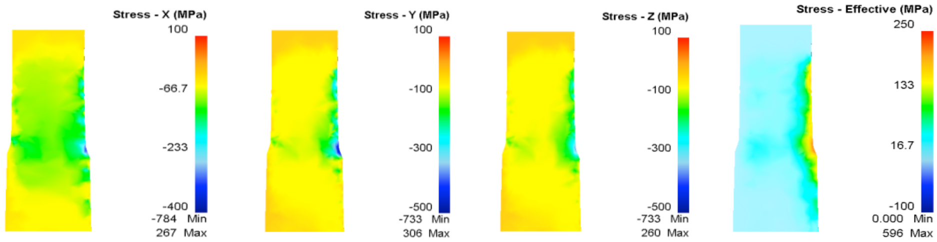
Fig.2 Stress field on cross section of stable rolling stage

Fig. 2(a) shows the distribution of transverse stress σ_x in the cross section of the part. At the stable initial rolling stage, the circular cross section starts to transit to a polygon due to that the bar has been completely into the three roll pass. It is observed that the distribution of compressive stresses occur at the three contact zone. Maximum value about - 425 MPa appears at the contact point. The compressive stress will become smaller if it is farther away from the contact area. However, the contact adjacent region will be affected by the tensile stress, which is quite common characteristics in three-roll skew rolling deformation.

Fig.2(b) shows the distribution of the stress σ_y in the cross-section of the part. As the process proceeds, the compressive stress in contact area is getting larger , which is ranged from - 500 MPa to - 700 MPa. It is also observed that tensile stress zone shrinks due to the spreading of compressive stress in the radial direction.

Fig.2(c) shows the distribution of axial stress σ_z in the cross-section of the part. Similar to Fig. 3(a) and (b), compressive stress occurs at the contact area, the most of the rest area is the distribution of tensile stress. The metal at the outer layer squeezed by roller will flow along axial direction ,which has the small resistance to flow. This will result in tensile stress of the metal at the outer layer of the part and cause the axial flow of metal,.

The distribution of equivalent stress $\overline{\sigma}$ in the cross-section of the part is shown in Fig. 2(d) . The equivalent stress intensity of part gradually decreases from outer surface to the center, and the maximum equivalent stress is 250 MPa, the minimum equivalent stress is at the center of rolled pieces for three-roll skew rolling. The forces generated by three-roll skew rolling act uniformly on the part, which is helpful to reduce the radial size and extend along axial direction. .



(a) Transverse stress σ_x (b) Longitudinal stress σ_y (c) Axial stress σ_z (d) Equivalent stress $\overline{\sigma}$

Fig.3 Stress field on longitudinal-section of stable rolling stage

Fig.3（a）shows the distribution of transverse stress σ_x at the longitudinal cross section of the part. It is observed that the compressive stresses are distributed in the most portion of the longitudinal cross-section. The compressive stress has penetrated into the rolled piece, its value is ranged from -60 MPa to -100 MPa. In practical, the metal has fully filled into three roll passage during stable rolling stage. The rolled metal is acted by force in all directions. As the rolling proceeds, the compressive stress will permeate gradually into bar from outer to inner.

Fig. 3(b) shows the distribution of the radial stress σ_y at the longitudinal cross-section of the part. It is observed that the compressive stress at the roller entrance and roller shoulder is greater than that of other area. The maximum value of compressive stress -200MPa. The stress value gradually decreases inward to the smaller value of -100 MPa. This is because the effect of roller on bar is obvious at the roller shoulders and thus will result in the maximum compressive stress value.

Fig. 3(c) shows the distribution of the axial stress σ_z at the longitudinal section of the part. It is observed that the distributed compressive stress is obvious and gradually decreases inward . Its value in between -300 MPa and -100 MPa. This will result in metal deformation to extend along the axial direction.

Fig. 3(d) shows the distribution of the equivalent stress $\overline{\sigma}$ at the longitudinal section of the part. It is observed that the local contact stress value is the largest, up to 250 MPa, which is named as the largest stress intensity . It is , gradually weakened and finally reduced to zero. The distribution of the stress suggest that metal flow along axial direction will benefit to the axial extension of the part.

6.Three-roll skew rolling bar orthogonal experiment design

Orthogonal experimental design using orthogonal table to select the representative strong test conditions, use to analysis the comprehensive comparison on the test results.

6.1 Experimental determination of parameters

Bar spiral tracks in the three-roll skew rolling is a very common phenomenon. The finite element simulation of rolling screw rod surface marks as shown in figure 4, this is due to the action of three-roll skew rolling roll Angle, roll friction of bar bar axis at the same time also will be around its own axis forward movement, the metal deformation area will generate additional axial shear deformation and torsion deformation, three roll is bound to be left in the surface of the bar under the pressure of the spiral tracks, this kind of thread trace can not disappear completely, but through the optimization of rolling technology and can effectively reduce the spiral tracks. Study on the average distance between rolling bar spiral mark as test index, spiral mark small average spacing optimization goal for this test. Applying bar placed, DEFORM-3D ruler in post-processing function measuring the distance between the two spiral mark, measuring average after multiple spiral mark spacing.

During three-roll skew rolling, the initial temperature, deflection Angle, roll angular velocity is the important process parameters affecting the quality of three roll skew rolling.In this paper, the author studies on titanium alloy bars the rolling forming process, the selected process parameters: the initial temperature (A) , deflection Angle (B), roll angular velocity (C).In the range of factors should be in the actual production experience within the scope of each factor in three levels, the level of the three factors values shown in table 3.

Tab.3 Experimental factors and factor levels

Factor	Level 1	Level 2	Level 3
initial temperature（A）/°C	900	950	1000
deflection Angle（B）/°	8	9	10
roll angular velocity（C）/rad/s	5	10	15

6.2 Range analysis results

By range analysis can directly influence on process parameters of three roll cross rolling spiral mark on average spacing.The test data and range analysis are shown in Table 4.

Tab.4 Range analysis in orthogonal test

Number	Factor level settings			average distance
	（A）/℃	（B）/°	（C）/rad/s	
1	1(900)	1(8)	1(5)	30.4254
2	1	2(9)	2(10)	30.2457
3	1	3(10)	3(15)	31.5452
4	2（950）	1	2	30.6178
5	2	2	3	31.7856
6	2	3	1	32.5547
7	3（1000）	1	3	30.4572
8	3	2	1	32.3524
9	3	3	2	32.5247
T1	92.2163	91.5004	95.3325	
T2	94.9581	94.3837	93.3882	282.5078
T3	95.3343	96.6246	93.788	
t1	30.73	30.50	31.77	
t2	31.65	31.46	31.13	
t3	31.77	32.21	32.26	
Optimum level	1	1	2	
R	3.118	5.1242	1.9443	
Order	B、A、C (B>A>C)			

In this experiment, the average distance between spiral mark as a single index by the range analysis.T_i is a column corresponding to section i of the target value of factors and levels.The Range R value is greater, the greater the influence that the process parameters on the average pitch spiral mark,Influence of forming on the surface of the metal bar is also larger.Can be based on the test results of the poor to determine the size of the effect of technical parameters on the spiral mark average spacing progression,As can be seen from table 4 various technological parameters of extreme value R2 > R1 > R3, so the effect of technical parameters on the screw marks the average distance between primary and secondary order to B, A, C.Explain the deflection angle change for adjusting spiral mark average spacing is the key。The best level combination resulting process parameters for three roll skew rolling:The initial temperature is 900℃, the deflection angle is 8°, the roll angular velocity is 10 rad/s.

By the process parameters and test index and T value change trend can be seen that the initial temperature of rolled pieces in spiral mark minimum average spacing, with the temperature increases, the spiral mark average spacing increases gradually, so the initial temperature of rolled pieces is unfavorable and exorbitant.With the increase of deflection angle, the more obvious the spiral traces，This is due to the deflection angle increases with the deformation zone is shortened, rolling force increases, roll in the horizontal direction velocity increase.Increase the amount of billet at every turn under pressure,this will make the bar in the rolling deformation in-homogeneity, cross section triangle effect, bar section roundness error increase.Effect of test indexes and change trend can be seen from the roll angular velocity，as the roll angular velocity changes，test index and T value first decreases then increases.When the roll angular velocity in 10 rad/s, spiral mark T value minimum average spacing, roll speed should be controlled within a certain range, should not be too big or too small.

7.Conclusion

(1)Finite element numerical simulation analysis of the titanium alloy rod three-roll skew rolling deformation zone distribution regularity of stress field, strain field and demonstrate the feasibility of titanium alloy rod three-roll skew rolling, by optimizing the rolling process parameters can improve the quality of three-roll skew rolling bar finished product;

(2)Through the analysis of range to determine the primary and secondary order effects of three parameters on the average spacing bar spiral mark for:Work-piece deflection angle, initial temperature, roll angular velocity.The best combination of the process parameters as the initial temperature of work-piece is 900℃, the deflection angle is 8°, the roll angular velocity is 10 rad/s.

8. Acknowledgements

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