



Optimization of extrusion process parameters of Incoloy028 alloy based on hot compression test and simulation

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Abstract: True stress–true strain curves of Incoloy028 alloy at high temperature and strain rate were investigated by hot compression test. These curves show that the maximum flow stress decreases with the increase in temperature and the decrease in strain rate. FEM simulation was employed to investigate the influence of temperature, extrusion speed and friction coefficient on the extrusion load, stress, strain and strain rate in the extrusion process. The increase of extrusion temperature results in decrease of load and deformation resistance, but has little influence on strain and strain rate. When extrusion speed changes between 200 and 350 mm/s, no obvious change about extrusion load can be found. Sharp peak value up to 42500 kN emerges in the extrusion load curve and the extrusion process becomes unstable seriously when extrusion speed rises up to 400 mm/s. Both stress and strain rate increase with the raise of extrusion speed. When friction coefficient is between 0.02 and 0.03, deformation resistance is about 160 MPa and the strain rate can be limited below 70 s^{-1} . Successful production of Incoloy028 tube verifies the optimized parameters by FEM simulation analysis, and mechanical tests results of the products meet the required properties.

Key words: Incoloy028 alloy; hot extrusion; compression; process parameter; FEM simulation

1 Introduction

In the severe and complex corrosive oil and gas wells with high temperature and high pressure as well as with high H_2S , CO_2 , Cl^- , and organic sulfur [1], the tube must meet the requirements of good physical and mechanical properties and high corrosion resistance. Traditional stainless steels, such as 9Cr [2], 13Cr [3], 22Cr [4], 25Cr [5] are difficult to serve in this harsh environment. Therefore, it is necessary to investigate a potential application of nickel-based alloys containing high content of chromium, nickel and molybdenum as an oil well tube material.

Incoloy028 (Fe–Ni–Cr–Mo) alloy is a low carbon austenite alloy [6], in which the copper content is about 1% (mass fraction). Because of low carbon content and high contents of chromium, molybdenum and copper, its comprehensive corrosion resistance and chloride ion stress corrosion resistance are good, and more, the intercrystalline corrosion resistance is excellent. However, it is difficult to adopt the method of hot

piercing process for Incoloy028 alloy due to its large hot deformation resistance. Because hot extrusion process is the only method at present, the plastic deformation can be completed in a short period at high temperature by controlling the extrusion process parameters.

The preliminary studies on Incoloy028 alloy mostly have been focused on the corrosion resistance. LIN et al [7] studied the effects of sensitizing heat treatment on precipitated phases and intergranular corrosion resistance of Incoloy028. CAI et al [8] contrasted the corrosion resistance of super13Cr and Incoloy028. Few researchers studied the hot working behavior. WANG et al [9,10] studied the dynamic recrystallization behavior of Incoloy028 by compression at temperature from 1273 to 1473 K and strain rates from 0.1 to 1 s^{-1} . Moreover, they also studied the flow stress based on compression tests. SUN et al [11] studied the deformation behavior and processing maps of Incoloy028, and modeled with the thermal general constitutive equations developed by SELLARS and TEGART [12]. There are no researches on hot extrusion deformation of Incoloy028 tube, especially on the key

parameters, such as the temperature, extrusion speed and friction coefficient, which have significant influences on extrusion load, stress, strain and strain rate. In this work, the hot extrusion behaviors in different hot working conditions were investigated by means of compression test, simulation and factual productive experiment.

2 Experimental

2.1 Materials

The chemical compositions (in mass fraction, %) of Incoloy028 alloy used in this study were: Ni 30–34, Cr 26–28, Mo 3–4, Mn <2.5, Si <1, Cu 0.6–1.4, P <0.03, S <0.03, and balance Fe. The raw material was a die-cast ingot produced by electro-slag re-melting process. The bar-shaped billet with a diameter of 400 mm was made by forging the cast ingot with a radial forging machine (GFM1800). In order to reduce the precipitate phase of Incoloy028 billet, the solid solution treatment at 1423 K was adopted after forging process.

2.2 Compression tests

Cylindrical specimens (10 mm in diameter and 15 mm in height) for compression tests were cut and machined from the forged bar. Hot compression tests were conducted on a Gleeble–3800 thermo-mechanical simulator in the temperature range of 1223–1473 K with intervals of 50 K at different strain rates ranging from 0.1 to 50 s⁻¹. The top and bottom surfaces of specimens were coated with graphite/Teflon paste to reduce the friction between anvil and specimens. All the specimens were heated up to 1473 K at a heating rate of 5 K/s and held for 3 min to obtain uniform microstructure. The specimens are then cooled down to different testing temperatures at a cooling rate of 5 K/s and held for 2 min prior to every test, and deformed to the height of 7.5 mm (50% reduction in height) corresponding to a true strain of 0.69 and then the compressed specimens were water-quenched to room temperature immediately. The strain and stress values obtained could be arranged to outline true strain–stress curves.

2.3 Hot extrusion deformation simulation

In this work, Incoloy028 alloy was produced by importing the true stress–strain curves of hot compression deformation acquired by compression tests into the material library of DEFORM-2D. The geometrical model was developed by CAXA package and then also imported into DEFORM-2D package. Figure 1 shows the extrusion model. Extrusion billet, container and die models were developed on the scale of 1:1. The container diameter was $d400$ mm, the billet dimension was $d400$ mm/ $d225$ mm, the mandrel diameter was $d210$ mm, and the lubrication of glass pad was replaced by friction coefficient [13].

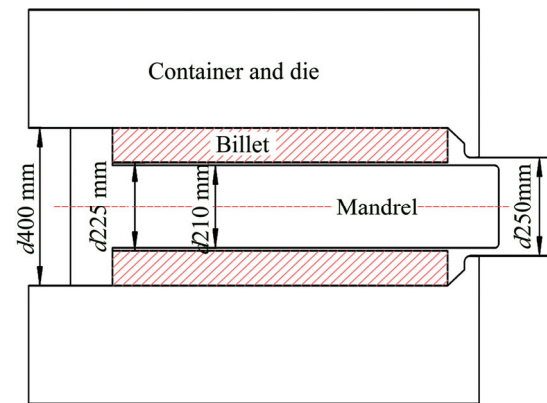


Fig. 1 Extrusion model of $d250$ mm $\times$ 20 mm Incoloy028

Quadrilateral elements were used to mesh for billet. In order to improve simulation accuracy and efficiency, adaptive meshing technology was carried out in main deforming regions to ensure the quality of mesh. The minimum mesh dimension of the geometrical bodies should be less than 1/3 of the minimum geometric feature dimension of geometrical bodies.

The extrusion process of Incoloy028 tube with dimensions of $d250$ mm $\times$ 20 mm was simulated by DEFORM-2D. The extrusion mode was horizontal follow-up extrusion. The effects of key parameters, such as temperature, extrusion speed and friction coefficient on the extrusion load, stress, strain and strain rate were analyzed.

2.4 Productive experiments

The rotary furnace was used to heat the billet from room temperature to 1123 K slowly. Then, the billet was heated to target temperature by induction furnace quickly. The inside diameter of the billet was expanded from $d80$ mm to $d225$ mm by 20 MN vertical piercer, then the billet was extruded to tube with dimensions of $d250$ mm $\times$ 20 mm by 60 MN horizontal extruder. Figure 2 shows the diagrams of the 20 MN vertical piercer and 60 MN horizontal extruder.

3 Results and discussion

3.1 True stress–strain curves and microstructure of specimens

3.1.1 Flow stress behavior based on hot compression test

Based on the isothermal hot compression test results, the load–stroke curves obtained at different temperatures and strain rates are converted into true strain–stress curves. Figure 3 shows the typical flow stress curves of Incoloy028 at various temperatures (1223–1473 K) and strain rates (0.1–50 s⁻¹). Obvious viscoplastic behavior can be observed. The flow stress increases with the increase in strain. When the strain

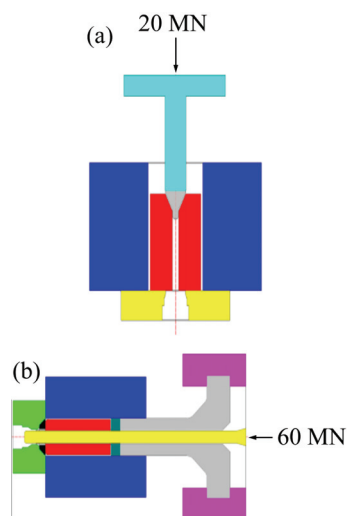


Fig. 2 20 MN vertical piercer (a) and 60 MN horizontal extruder (b)

risks to a certain value, the flow stress becomes stable and even decreases. Moreover, the evolution of all the flow stress curves follows the same trend, i.e., an increase at the initial stage followed by a gentle decrease or a plateau. The increase in the initial stress is caused by dislocation entanglement and pile-ups and the increasing

strain energy of deformed grains. The decrease in flow stress, particularly in the case of low strain rate (0.1 s^{-1}), is due to the combined effects of dynamic recovery and recrystallization, which lead to the dislocation annihilation. When a dynamic balance is achieved between the dislocation aggregation and annihilation, the flow stress plateaus could be observed. In the case of high strain rate (50 s^{-1}), dynamic recovery leads to the dislocation annihilation as a result of dislocation slipping and climbing.

3.1.2 Microstructure of specimens after compression test

Figures 4(a)–(d) show the microstructures of specimens at the temperature of 1373 K and the strain rate of $0.1\text{--}50 \text{ s}^{-1}$. Figures 4(e)–(h) show the microstructures of specimens at temperature of 1423 K and the strain rate of $0.1\text{--}50 \text{ s}^{-1}$. Figures 4(i)–(l) show the microstructures of specimens at temperature of 1473 K and the strain rate of $0.1\text{--}50 \text{ s}^{-1}$. At the same temperature, the greater the strain rate is, the smaller the recrystallization grain is. And the recrystallization grain becomes coarse with the increase of temperature. The increase of dislocation movement velocity results in the raise of recrystallization rate and degree. When the recrystallization grain meets requirements, the repeated recrystallization can take place, so the grain will be smaller and smaller.

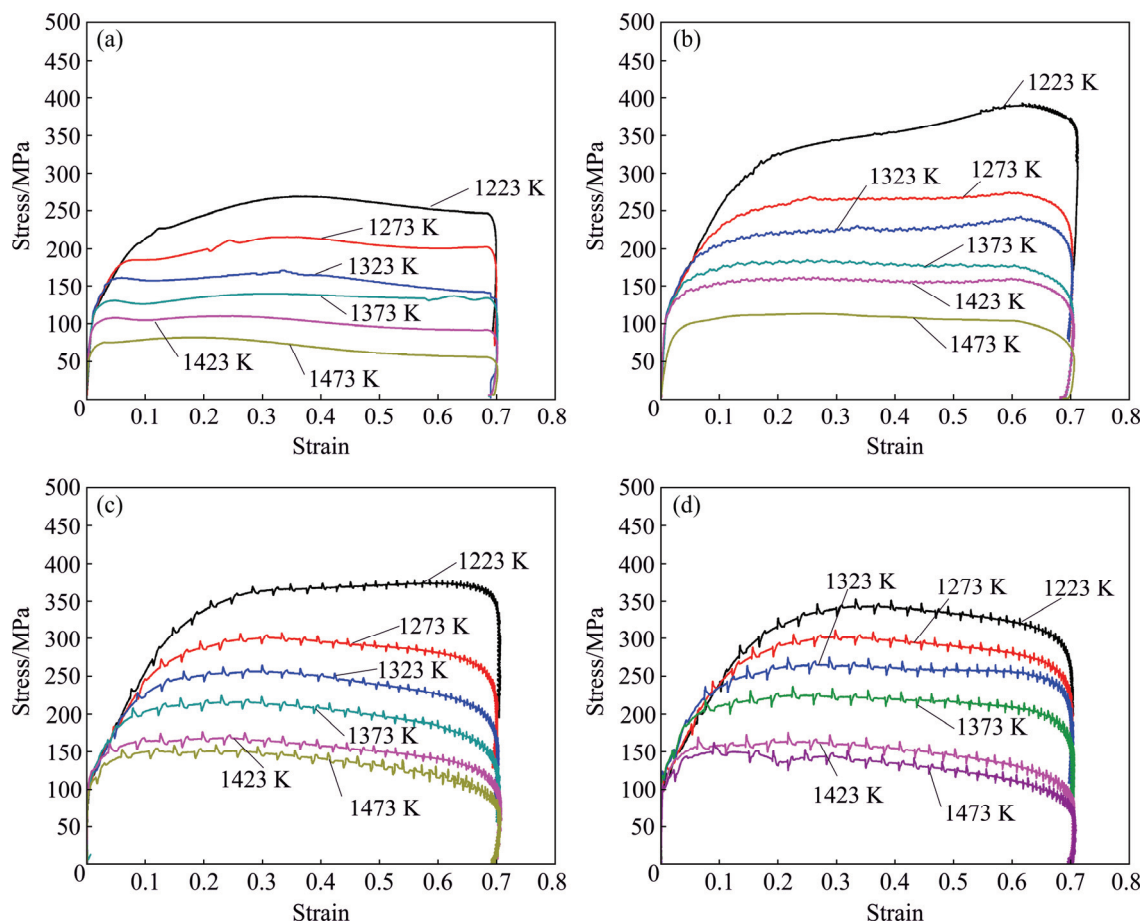


Fig. 3 Stress–strain curves of Incoloy028 at various temperatures and strain rates: (a) 0.1 s^{-1} ; (b) 1 s^{-1} ; (c) 10 s^{-1} ; (d) 50 s^{-1}

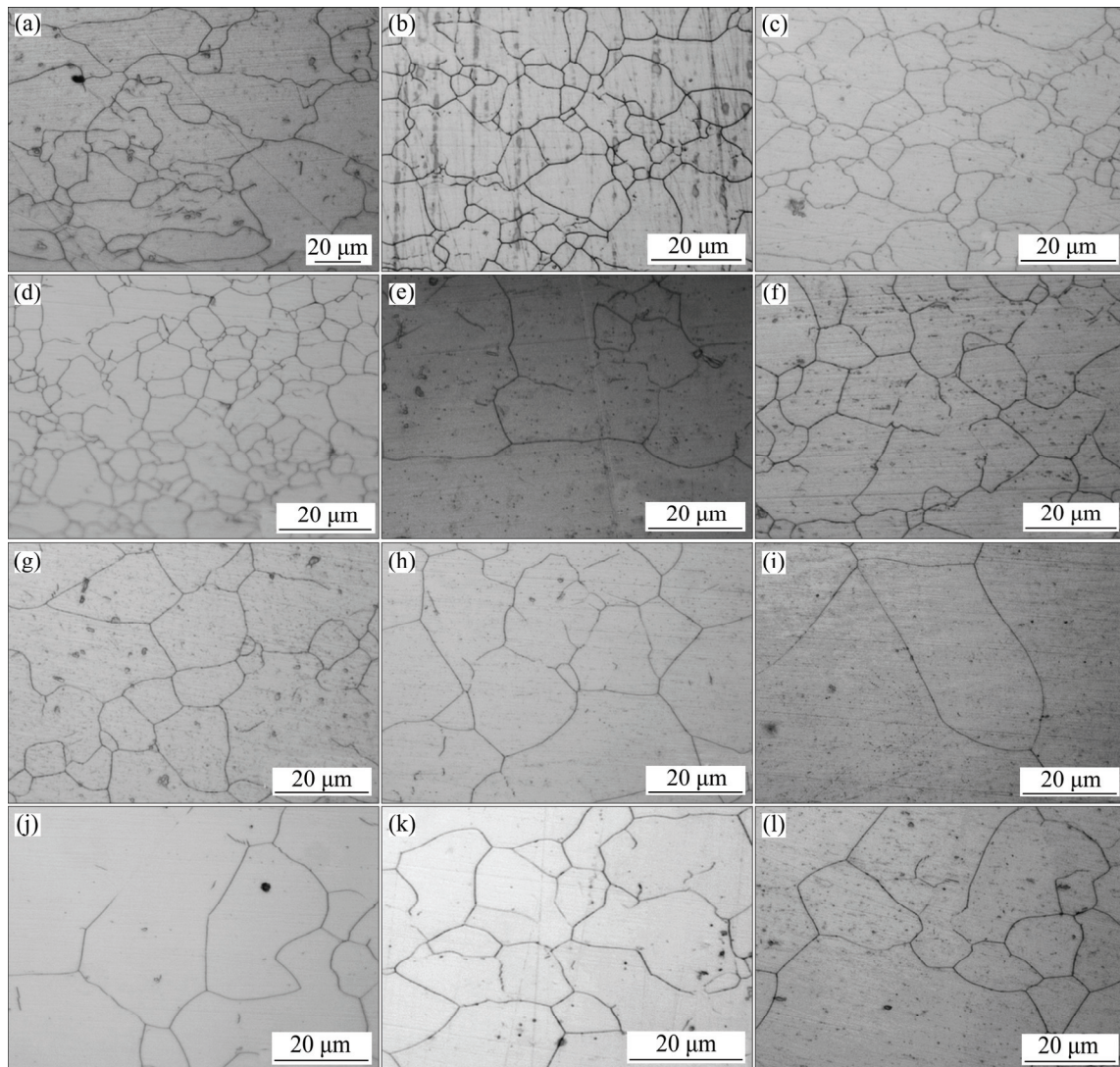


Fig. 4 Microstructures of samples at temperatures of 1373 K (a–d), 1423 K (e–h), 1473 K (i–l) and strain rates of 0.1 s^{-1} (a, e, i), 1 s^{-1} (b, f, j), 10 s^{-1} (c, g, k) and 50 s^{-1} (d, h, l)

3.2 Extrusion parameters of Incoloy028 by simulation analysis

When extruding steels and some difficult deformation metal, Sejour equation was used to calculate extrusion load [14]. In the extrusion process of tube, Eq. (1) was used to calculate extrusion load F :

$$F = \pi(R^2 - r^2)k \ln[\lambda \exp(\frac{2fL}{R-r})] \quad (1)$$

where R and r are the radii of container and mandrel, respectively, f is the friction coefficient, L is the length of the billet, k is the deformation resistance, and λ is the extrusion ratio.

In Eq. (1), proportional relationship exists between the extrusion load and deformation resistance, but deformation resistance is affected by temperature, and hot compression deformation test has preliminarily supported this view. The extrusion load has no direct

relation with extrusion speed, but has index relation with friction coefficient. Next, we used simulation method to analyze the relations among extrusion load, stress, strain, strain rate and temperature, extrusion speed and friction coefficient.

3.2.1 Effects of temperature on extrusion load

In order to analyze the temperature effect on the extrusion load, the extrusion speed and friction coefficient are set to be 250 mm/s and 0.02, respectively. The temperature is varied between 1423 and 1473 K. As shown in Fig. 5, the extrusion load decreases with the increase of temperature, which is consistent with the results of compression test.

With the purpose of analyzing the effect of the extrusion speed on extrusion load, suppose the temperature and friction coefficient are 1453 K and 0.03, respectively. As shown in Fig. 6, when the extrusion speed changes between 200 and 350 mm/s, no obvious

changes in the extrusion load can be found. The influence of extrusion speed on extrusion load acts through friction and temperature, the increase of the extrusion speed results in temperature rise (T') in the form of friction (f'), and temperature rise causes the decrease of deformation resistance. The effect of temperature rise and deformation resistance on extrusion load then will be offset each other, so the extrusion load does not change significantly, as described by Eq. (2)

$$Q_v = Q_{f'} - Q_{T'} \quad (2)$$

where Q_v is the energy caused by speed; $Q_{f'}$ is the energy caused by friction and $Q_{T'}$ is the energy caused by temperature rise.

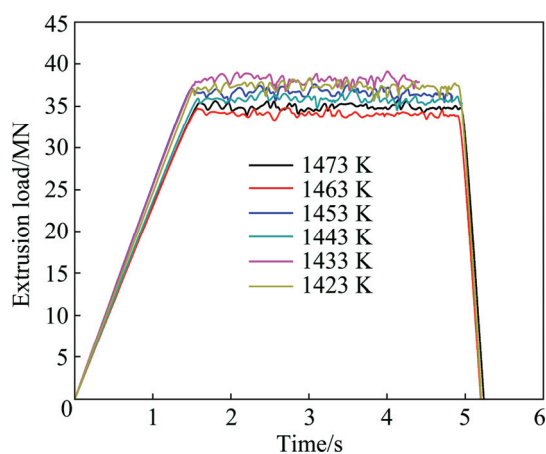


Fig. 5 Effects of temperature on extrusion load

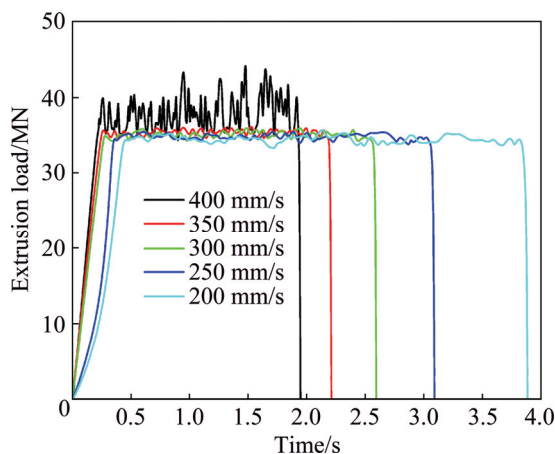


Fig. 6 Effects of extrusion speed on extrusion load

However, the sharp peak value up to 42.5 MN emerges in the extrusion load curve when the extrusion speed rises to 400 mm/s because $Q_{f'}$ is larger than $Q_{T'}$.

3.2.2 Effects of friction coefficient on extrusion load

In interest of analyzing the effect of friction coefficient on extrusion load, the temperature and friction coefficient are set to be 1453 K and 200 mm/s, respectively. As shown in Fig. 7, the extrusion load curve is relatively stable when the friction coefficient changes between 0.02 and 0.03. The friction coefficient has a

great influence on the extrusion load when it increases by ten times (0.2–0.3), and extrusion load value would increase by 10 MN and fluctuate severely. Therefore, the friction conditions must be controlled strictly to avoid overload. For reaching the friction coefficient of 0.02–0.03 [15], glass lubricant [16] is used.

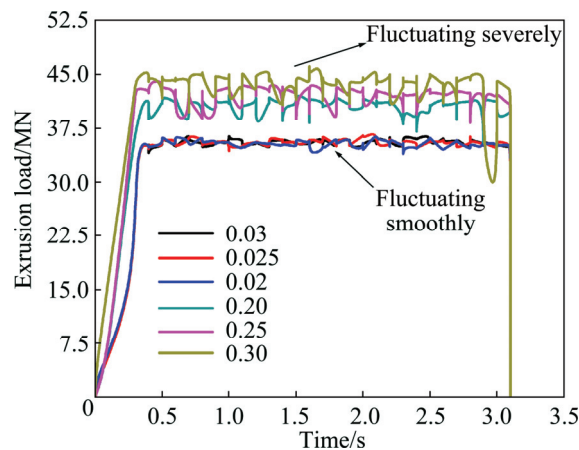


Fig. 7 Effects of friction coefficient on extrusion load

Figure 8 shows the simulation of extrusion process for Incoloy028 tube with dimensions of $d250 \text{ mm} \times 20 \text{ mm}$. Extrusion die and billet are rotational symmetry. As can be seen, deformation in the transitional region between container and die is acute, and hot extrusion process is accompanied with recrystallization.

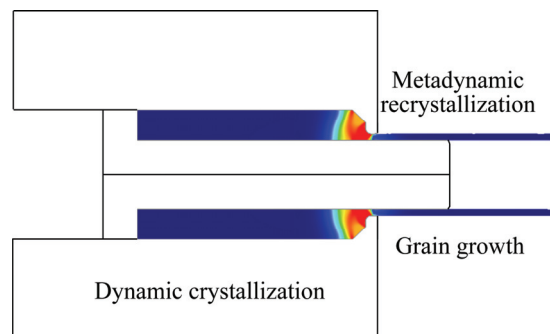


Fig. 8 Simulation model of Incoloy028 extrusion pipe

The hot extrusion process of Incoloy028 alloy can be divided into three different stages, upsetting, breakthrough and steady. Figure 9 shows the stress, strain and strain rate distribution at three different stages. At the upsetting stage, the container is filled by metal entirely. At the breakthrough stage, the metal outflows the extrusion die. At the steady stage, the metal flows out through the die hole smoothly.

3.2.3 Effects of temperature on stress, strain and strain rate

Similarly, in order to study the effects of the temperature on the effective stress, strain and strain rate, the extrusion speed and friction coefficient are fixed to

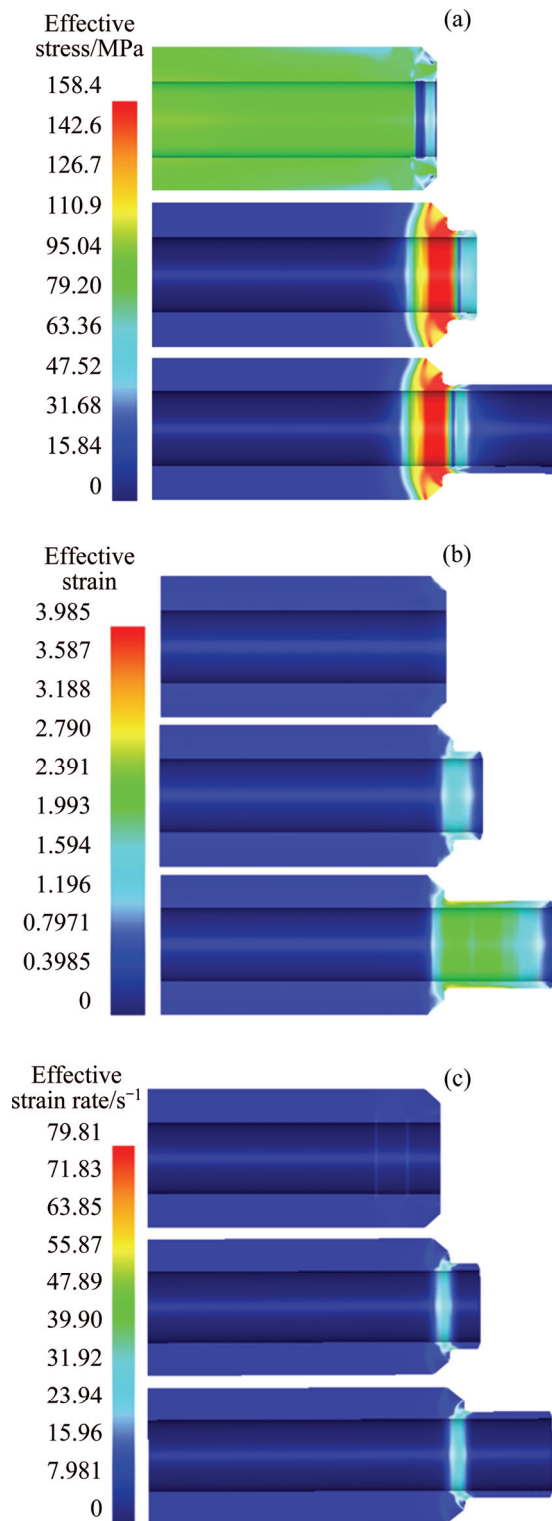


Fig. 9 Distribution of effective stress (a), strain (b) and strain rate (c) of Incoloy028 extrusion pipe

200 mm/s and 0.03, respectively. As shown in Fig. 10(a), all the stresses at the upsetting, breakthrough and steady stages decrease with the rise in temperature. At the upsetting stage, the stress decreases obviously. At the breakthrough and steady stages, the evolution trend of the stress is consistent with each other. If the stress is

regulated smaller than 160 MPa in steady stage, the extrusion temperature must be above 1453 K. As shown in Fig. 10(b), strain remains the same value at each stage, but it can be found that the strain at steady stage is greater than that at breakthrough stage, and the strain at breakthrough stage is greater than that at the upsetting stage. Figure 10(c) shows the strain rate varies with the temperature at three different stages. At the upsetting stage, the strain rate value is about zero. At the breakthrough and steady stages, the strain rates decrease with increasing temperature, if the strain rate is regulated

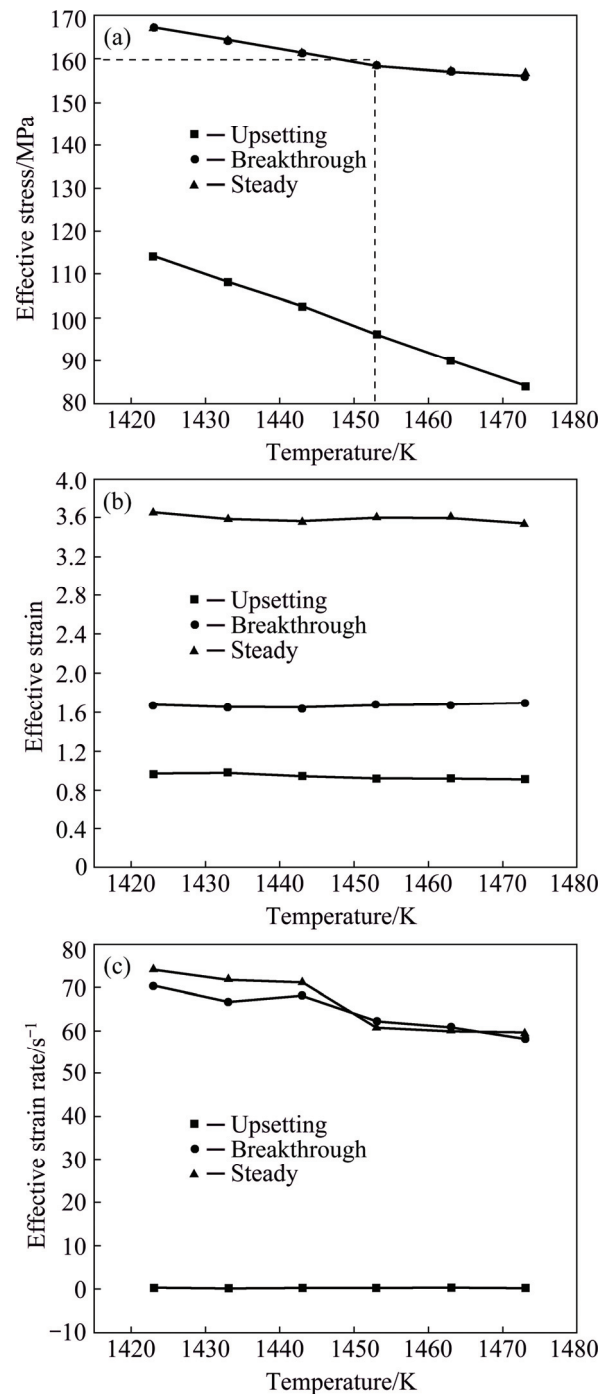


Fig. 10 Evolution of effective stress (a), strain (b) and strain rate (c) with temperature

under 60 s^{-1} at breakthrough and steady stages, the temperature must be above 1453 K.

SELLARS and TEGART [12] developed a hyperbolic sine function to describe the relationship between stress and strain rate at high temperature, as indicated in Eq. (3):

$$\dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = A [\sinh(\alpha\sigma)]^n \quad (3)$$

The relationship can be described by a power law (Eq. (4)) under low stress ($\alpha\sigma < 0.8$) and by an exponential relation (Eq. (5)) under high stress ($\alpha\sigma > 1.2$) conditions:

$$\dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = A_1 \sigma^{n_1} \quad (4)$$

$$\dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = A_2 \exp(n_2 \sigma) \quad (5)$$

where $\dot{\varepsilon}$ is the strain rate, σ is the flow stress, Q is the activation energy of deformation, A , A_1 , A_2 , n , n_1 , n_2 and α ($\alpha = n_1/n_2$) are material constants closely related to the strain rate, R is the mole gas constant, $8.314 \text{ J/(mol}\cdot\text{K)}$, T is the thermodynamic temperature. SUN et al [11] found the relationship between $\dot{\varepsilon}$, σ and T by Eq. (6):

$$\sigma_{\max} = \frac{1}{0.005} \operatorname{arsinh} \left[\exp \left(\frac{\ln \dot{\varepsilon} - 33.57 + 388298 / (RT)}{5.848} \right) \right] \quad (6)$$

3.2.4 Effects of extrusion speed on stress and strain rate

In order to analyze the effect of extrusion speed on stress and strain rate, the temperature and friction coefficient are set to be 1453 K and 0.03, respectively. As shown in Fig. 11(a), stress increases with the rise in extrusion speed, and all the stress values are more than 150 MPa. The stress at breakthrough stage is larger than that at steady stage at the same extrusion speed, especially when the extrusion speed increases to 400 mm/s, stress increases significantly. Figure 11(b) shows the evolution of strain rate with extrusion speed at breakthrough and steady stages. It is clear that strain rate increases with the rise in extrusion speed. When the extrusion speed reaches 200 mm/s, strain rates at breakthrough and steady stages are 55.56 and 51.83 s^{-1} , respectively. However, strain rate reaches up to about 100 s^{-1} when extrusion speed rises to 350 mm/s, and strain rate reaches up to 160 s^{-1} when extrusion speed rises to 400 mm/s at breakthrough stage, reflecting that non-uniform deformation is tempestuous when the extrusion speed increases to 400 mm/s. In order to ensure strain rate to be smaller than 60 s^{-1} in breakthrough and steady stages, extrusion speed should be under 225 mm/s. In order to ensure deformation resistance about 160 MPa in breakthrough and steady stages, extrusion speed should be under 375 mm/s.

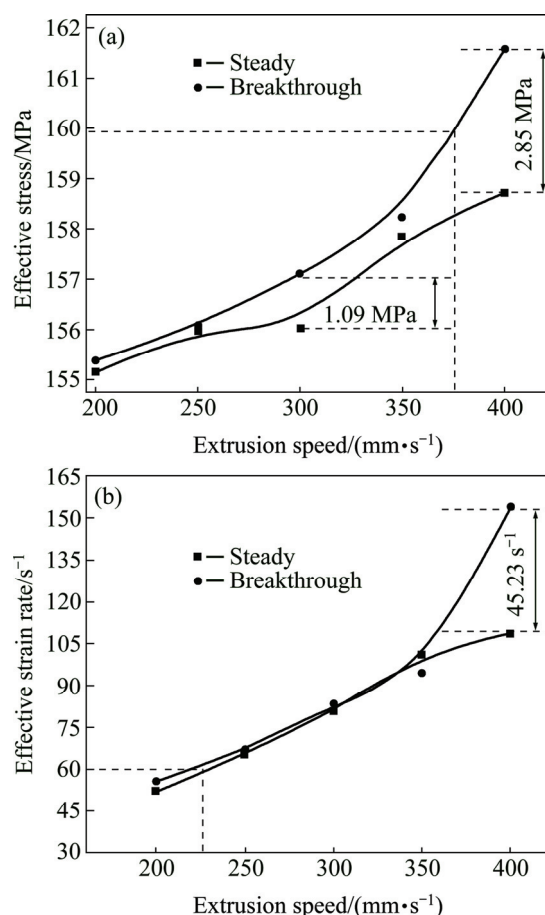


Fig. 11 Effective stress (a) and strain rate (b) with extrusion speed

3.2.5 Effects of friction coefficient on stress and strain rate

In order to analyze the effect of friction coefficient on stress and strain rate, temperature and extrusion speed are fixed as 1453 K and 250 mm/s, respectively. As shown in Fig. 12(a), stress increases with increasing friction coefficient at upsetting stage and the stress value is more than 125 MPa. The stresses keep almost the same values at breakthrough and steady stages. Figure 12(b) shows the evolution of the strain rate with friction coefficient at three different stages. At the upsetting stage, the strain rate value is close to zero; at the breakthrough and steady stages, the strain rate values keep very close with each other, between 60 and 70 s^{-1} . Thus, when the friction coefficient is between 0.02 and 0.03, the deformation resistance is about 160 MPa and the strain rate can be under 70 s^{-1} .

The effects of friction coefficient on metal flow velocity and displacement movement are shown in Fig. 13. When friction coefficient is set as 0.02, the maximum flow rate is 1790 mm/s, and the maximal displacement movement is 251 mm, as shown in Figs. 13(a) and (b). When friction coefficient is 0.2, the maximum flow rate is 1560 mm/s, and the maximal

displacement is 218 mm, as shown in Figs. 13(c) and (d). These reflect that the change of friction coefficient influences the metal flow absolutely, and the increase of friction coefficient can delay the metal flow.

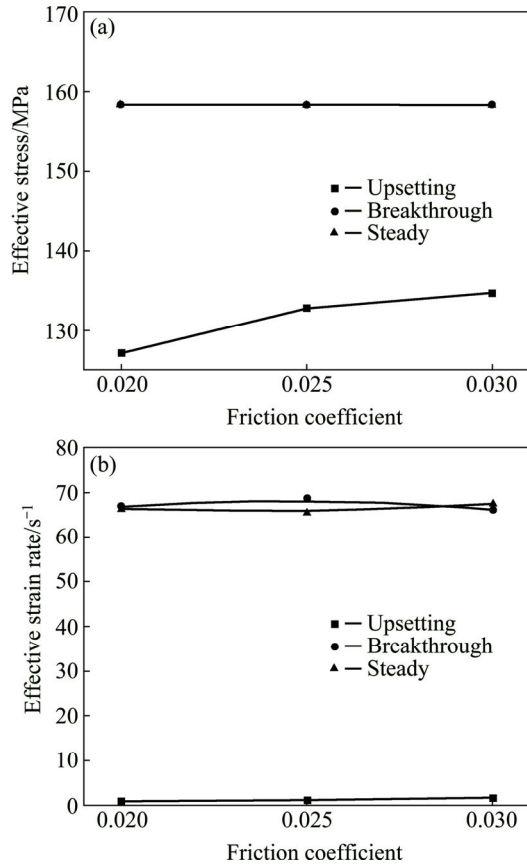


Fig. 12 Stress (a) and strain rate (b) with friction coefficient

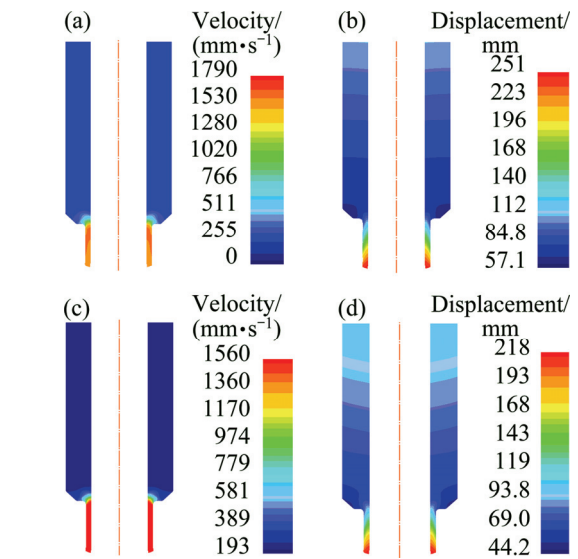
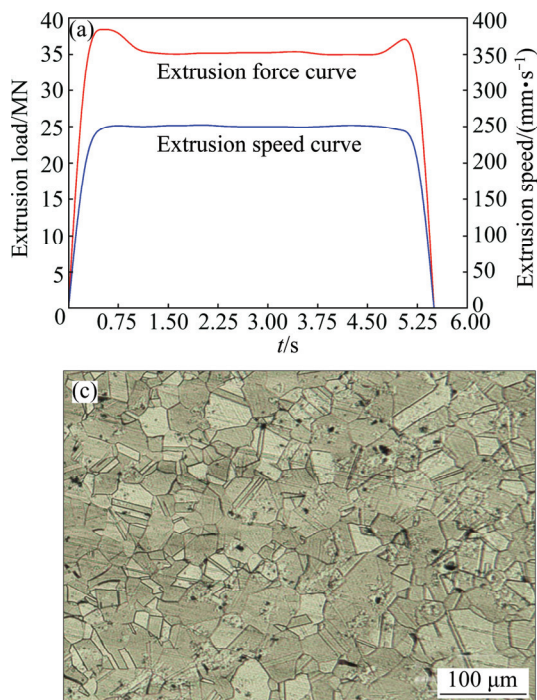


Fig. 13 Effect of friction coefficient and displacement on metal flow velocity: (a, b) Friction coefficient of 0.02; (c, d) Friction coefficient of 0.2

3.3 Productive experimental results of Incoloy028 based on simulation

Incoloy028 tube is manufactured successfully by 60 MN horizontal extruder [17] with temperature 1453 K, speed 250 mm/s and glass lubrication. As shown in Fig. 14(a), actual extrusion load and speed are similar to simulation results. Single-phase austenitic microstructure is observed in the internal, external and middle parts of the manufactured Incoloy028 tube, as shown in Figs. 14(b), (c) and (d), the grain grades are 5–6, 6 and

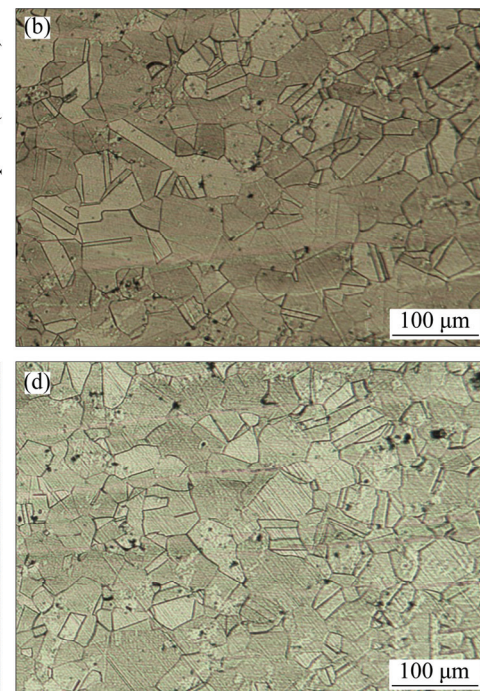


Fig. 14 Extrusion load and speed curves (a) and microstructures of internal (b), external (c) and middle (d) parts of tube

5–6, respectively. Table 1 shows mechanical properties of extrusion tube $d250\text{ mm} \times 20\text{ mm}$. The extrusion tube $d250\text{ mm} \times 20\text{ mm}$ is rolled to $d177.8\text{ mm} \times 9.19\text{ mm}$ by two times cold rolling process [18] and solution treatment. Table 2 shows mechanical properties of tube $d177.8\text{ mm} \times 9.19\text{ mm}$, which meets the requirements of ISO 13680 2010. Productive experiment results verify reasonable research on extrusion process parameters of Incoloy028 alloy based on isothermal compression test and simulation.

Table 1 Mechanical properties of Incoloy028 extrusion pipe ($d250\text{ mm} \times 20\text{ mm}$)

Yield strength/MPa	Tensile strength/MPa	Elongation/%	Brinell hardness
275	605	54	76.7

Table 2 Mechanical properties of Incoloy028 cold rolling pipe ($d177.8\text{ mm} \times 9.19\text{ mm}$)

Mechanical property	Requirement	Incoloy028 cold rolling pipe
Yield strength/MPa	758–955	785
Tensile strength/MPa	>793	860
Elongation/%	>11	22
Brinell hardness	<35	23.2
Impact power/J	>40	122

4 Conclusions

1) The deformation resistance and extrusion load of Incoloy028 alloy have inverse relation with temperature. If the stress is regulated to be smaller than 160 MPa in steady stage and strain rate is regulated under 60 s^{-1} in breakthrough and steady stages, the temperature should be above 1453 K.

2) When extrusion speed changes between 200 and 350 mm/s, no obvious change in extrusion load can be found. When extrusion speed rises up to 400 mm/s, sharp peak value up to 42.5 MN emerges in the extrusion load curve. Both the stress and strain rate increase with the raise of the extrusion speed. In order to ensure strain rate to be smaller than 60 s^{-1} in breakthrough and steady stages, extrusion speed should be under 225 mm/s. In order to ensure deformation resistance about 160 MPa in breakthrough and steady stages, extrusion speed should be under 375 mm/s.

3) When the friction coefficient is between 0.02 and 0.03, the deformation resistance is about 160 MPa and the strain rate can be under 70 s^{-1} . The change of friction coefficient influences the metal flow absolutely, and the increase of friction coefficient will delay the metal flow.

4) Incoloy028 tube is manufactured successfully

based on simulative results. Uniform and dense austenitic microstructures are observed in internal, external and middle parts of Incoloy028 tube, and the mechanical properties meet the requirements after cold rolling process and solution treatment.

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基于热压缩试验与模拟的 Incoloy028 合金挤压工艺参数优化

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摘 要: 采用热压缩实验方法研究 Incoloy028 合金在高温和高应变速率下应力-应变曲线。应力-应变曲线表明, 峰值应力随着温度的升高和应变速率的下降而降低。采用有限元模拟方法研究挤压过程中温度、挤压速度和摩擦因数对挤压载荷、应力、应变和应变速率的影响, 提高挤压温度可以降低挤压载荷和变形抗力, 但对应变和应变速率的影响较小。当挤压速度在 200~350 mm/s 之间变化时, 挤压载荷没有发生明显变化; 当挤压速度达到 400 mm/s 时, 挤压突破力达到 42500 kN, 挤压过程极不稳定。随着挤压速度的增大, 应力和应变速率增大。当摩擦因数在 0.02~0.03 之间变化时, 变形抗力约为 160 MPa, 挤压过程中应变速率可以控制在 70 s^{-1} 以下。生产试验成功验证了采用有限元方法优化后的挤压工艺参数, 产品的力学实验结果满足性能要求。

关键词: Incoloy028 合金; 热挤压; 压缩; 过程参数; 有限元模拟

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