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Titanium crank forging mould design and validation

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Abstract: In this paper, we carry out research on the forging process of titanium crank for an offshore equipment, and put forward two options of die-splitting surface design through structural analysis, and choose the transverse die-splitting option (Option 2) by taking into account the forming quality and material utilisation rate. Based on the complexity coefficient of the forging part, the machining allowance (1.5mm), the inclination of the extracting die (3 ° on the outer surface and 5 ° on the inner surface) and the radius of the fillet (1mm) are calculated, and the design of the forging part drawing is completed.Combined with the thermal expansion characteristics of TC4 titanium alloy, the coefficient of cold shrinkage was determined to be 0.5%, and the hot forgings were designed and the parameters of the flying edge groove were optimised (height of the bridge section 0.97mm, width 8mm).Numerical simulation of the forging process was carried out using Deform software, and the results showed that the temperature field was uniform, the material flow was reasonable, the maximum forming load was 5180kN, and no folding or filling defects were found.The actual production verification shows that the finished forgings have no cracks, folding and other defects, and the forming quality meets the design requirements, which provides technical guidance for the efficient forging of titanium alloy cranks.

1. Introduction

Since the United States successfully developed a practical titanium alloy (Ti-6Al-4V) in 1954, titanium and titanium alloys have been widely used in aerospace, marine vessels and other fields by virtue of their high strength, corrosion resistance and other characteristics[1].In recent decades, the application development of titanium alloys in China has made remarkable progress. With the continuous progress of technology and the growth of demand, the application fields of titanium alloys are gradually expanding in the country, becoming an important high-performance material.As a key component in mechanical systems, cranks are widely used in internal combustion engines, pedal cars, steam engines, all kinds of mechanical equipment and some complex mechanical systems.As a kind of rotating element, the crank plays an important role in the mechanical structure, such as converting the form of motion, force transmission, power output and reducing vibration.

This paper takes a titanium alloy crank for an offshore equipment as the research object, through the structural analysis of the crank forging, designs the suitable forging process mould, and combines with the computer finite element simulation technology, simulates the forging process, verifies the feasibility of the mould design, and provides technical guidance for the actual production of forging parts.

2. Crank forging mould design

2.1 Structural analysis of parts

Crank parts shown in Figure 1, its structure has the following characteristics: First, the appearance of the part is a long axis type, with a large aspect ratio, in the forging process is easy to produce bending or even broken.Second, the parts tail rib plate thickness is small, but the area is large, which will lead to forging filling difficulties, and will produce a large flying edge, affecting the material utilisation.Third, the parts of the tail and the middle of the connecting area of the angle is small, the forging process of material flow in the opposite direction, may produce folding and other defects.

Fig. 1 Crank part drawing

2.2 Crank forging drawing design

(1) Design of the parting face of a forging

The design of forging parting surface is crucial to the quality of forgings and production efficiency, a reasonable parting surface should be preferred in the symmetrical surface of forgings or easy to separate the area to reduce the risk of clamping, while avoiding thin-walled, complex structure area to reduce die wear and material waste.It is necessary to avoid the key working surface or appearance surface directly contacting the mould to prevent surface defects such as scratches, indentations, etc., and optimize the design of parting surface according to the direction of material flow to ensure the mould cavity is filled evenly and smoothly[2].

The shape of the part studied in this paper is in the form of a long axis.According to the structural characteristics of the part, two ways of dividing the mould are designed, as shown in Fig. 2.Option 1 is longitudinal forging, and the parting surface is set at the rib plate at the tail of the part.This scheme mainly forges the tail part locally, which is convenient for the material to fill the mould, but it increases the difficulty of demoulding and reduces the production efficiency, and at the same time leads to the uneven properties of the head and rod part of the part.Option 2 is transverse forging, the parting surface is set at the maximum projected area of the part.This option is to forge the part as a whole, but the area of the ribbed plate at the end of the part is larger and thinner, which can lead to difficulty in filling the forging and produce a larger flying edge, which in turn reduces the utilisation of the material.After comprehensive consideration, in order to ensure the uniformity of the part performance, the die splitting method of Option 2 is selected.

(a) (b)

Fig.2 Parting surface, (a) scheme 1, (b) scheme 2

(2) Machining allowances for forgings, die pulling slopes and fillet radii

To determine the machining allowance and fillet radius of the forging, it is first necessary to calculate the shape complexity coefficient S of the forging, and the calculation formula is shown in equation (1).

$$S = \frac{G}{H} \tag{1}$$

Formula: *G*——Volume of forgings, mm3;

H——Volume of the outer containment body of the forging, mm3.

The basic dimensions of the parts drawing are used to estimate the machining allowances, and then the forging is drawn to estimate the volume of the forging. The volume of the crank forging is G=20590.49mm3, the volume of the forging's outer containment body is H=72277.73mm3, and the complexity coefficient of the forging can be calculated by substituting into Eq. 1 as S=0.285. Checking the relevant information, the machining allowance of the crank forging is 1.5mm, the slant of the outer surface of the extractor is 3 °, the slant of the inner surface of the extractor is 5 °, and the radius of the rounded corner is 1mm.

By analysing the crank part drawing and combining the parameters obtained, the forging of the crank is drawn as shown in Fig. 3.

Fig.3 Forging diagram for crank

2.3 Design of crank final forging mould

According to the different forging methods, the dies can be divided into open die forging dies and closed die forging dies.Considering the structural characteristics of the crank parts, the crank forging die selects the open die forging die.

(1) Design of hot forgings

The forming method of crank is hot die forging, the size of the forging will be reduced after it is taken out of the forging mould and cooled to room temperature, the cold shrinkage coefficient of titanium alloy forging mainly depends on its linear expansion coefficient and the temperature change during forging[3], the cold shrinkage coefficient can be calculated by the temperature change and the linear expansion coefficient as shown in equation (2).

$$\sigma = \rho \times \Delta T \times 100\% \tag{2}$$

Formula:σ——Cold shrinkage coefficient;

ρ——Coefficient of linear expansion, °C^{-1};

ΔT——temperature change, °C.

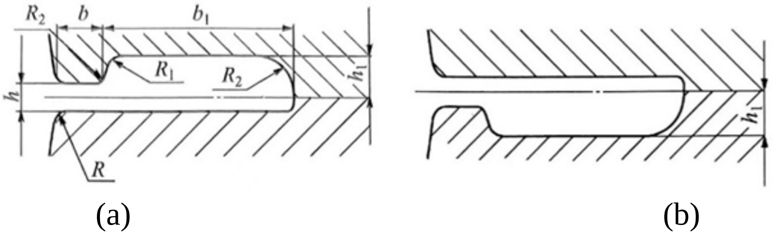
The linear expansion coefficient of TC4 titanium alloy is about 8.6×10-6 / ℃, and the temperature change is about 900 ℃. Substituting into equation 2.1, the cold shrinkage coefficient of TC4 titanium alloy is calculated to be 0.774%.Considering the thermal expansion of the mould material, the cold shrinkage coefficient is taken as 0.5%.According to the obtained cold shrinkage coefficient, the forging is scaled up to get the hot forging, as shown in Fig. 4.

Fig.4 Diagram of crank hot forging

(2) Types and sizes of fretting grooves

The perimeter of the final forging die for open die forging must be provided with a fretted groove.This structure serves three key purposes: first, it increases the resistance to the outward flow of the metal material.This resistance helps the metal to fill the die chamber.Secondly, the fretting groove also accommodates excess metal.The fret also acts as a cushion during the forging process.It mitigates the impact between the upper and lower dies.This cushioning protection prevents the die from collapsing or cracking.In addition, the thickness of the fretted part is usually relatively thin.This design feature has two advantages: on the one hand, it reduces material waste, and on the other hand, the fret can be easily removed later with ordinary equipment[4].

The fretting groove generally consists of a bridge section and a bin section, and there are two common types of fretting grooves, as shown in Figure 5.Figure 5(a) shows the standard type of fretting groove structure, which is the most commonly used type.The bridge section of this structure is set at the upper die position.The upper die is heated for a shorter period of time during the forging process and the temperature rise is smaller.Due to the lower temperature, the bridge structure is less likely to be crushed and also effectively reduces the degree of wear on the bridge part.Figure 5(b) shows an inverted shaped flying edge groove structure.This structure is mainly used in two cases: the first case is when the upper die structure of the forging piece is relatively complex, the use of this design can simplify the shape of the trimming punch.Because the workpiece needs to be turned over to cut the edge, the inverted structure can better match the operation.The second case is when the upper die has no cavity at all.In this case, all the moulding structure is concentrated in the lower die, and the use of inverted flute can make the mould production simpler.



(a) (b)

Fig.5 Types of common fretting grooves

There are two common methods for designing the dimensions of the fretting groove, namely the tonnage method and the calculation method. The tonnage method is based on the tonnage of the equipment to determine the size of the fretting groove; the calculation method is based on the projected area of the forging on the parting surface, and then through the empirical formula to calculate the height of the bridge, and then determine the other relevant dimensions. Considering that the determination of the size of the fretting groove through the tonnage method only takes into account the tonnage factor of the equipment, which is less accurate, so this paper chooses the calculation method to determine the size of the fretting groove, and the empirical formula is shown in equation

(3).

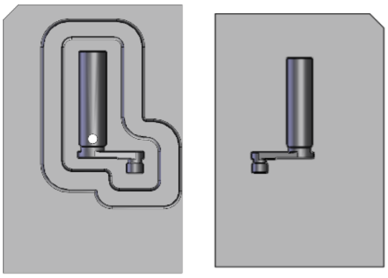
$$h = 0.025\sqrt{S} \tag{3}$$

Formula:h——height of the flysheet bridge section, mm;

S——Projected area of the forging on the parting face, mm^3.

The projected area of the crank forging on the parting surface is 1499.76mm2, substituting into equation 3, the height of the bridge part of the fretting slot is calculated as 0.97mm, and the other dimensions of the fretting slot are determined by consulting the relevant information.The width b of the bridge part of the fly-edge slot is 8mm, the height h1 of the bin part is 4mm, the width b1 of the bin part is 22mm, and the rounded corner R is 1.5mm.

Combined with the above data, the crank final forging mould is drawn, as shown in Fig. 6.

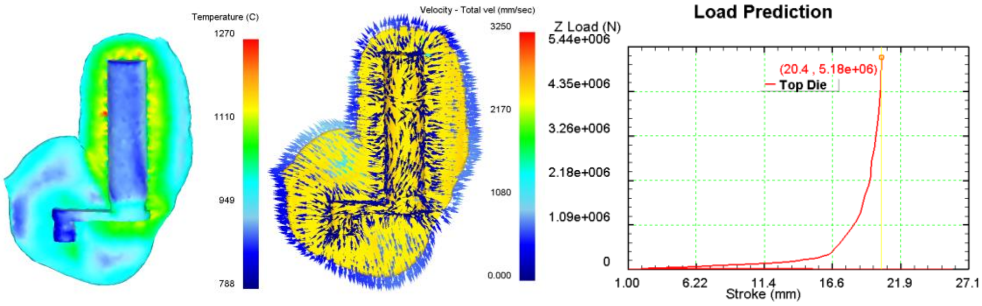


(a) (b)

Fig. 6 Crank final forging die (a) upper die, (b) lower die

3. Numerical simulation of forming processes

The designed forging drawing and die drawing were output into STL format and imported into Deform software for finite element numerical simulation. The specific process flow is as follows: the bar with a diameter of 20mm and a length of 94mm is heated to 950 ℃ for bending billet; then the bent part is placed on the final forging die with a preheating temperature of 300 ℃ for final forging; and finally, the edge-cutting process is carried out. The simulation results are shown in Fig. 7. From Fig. 7(a), it can be seen that the temperature of the bridge part of the fly edge is higher due to the violent flow of material, and the temperature of the main part of the forging part is uniform. The velocity field vector direction is uniform in Fig. 7(b), and the flow direction is as expected. The maximum forming load of the upper die in Fig. 7(c) is 5180 kN. no obvious forging defects, such as folding and incomplete filling, are found in the simulation.



(a) (b) (c)

Fig. 7 Numerical simulation results (a) temperature field, (b) velocity field, (c) forming loads

4. Production Verification

According to the analysis of the simulation results, the simulation results were verified in actual production.The billet used in the actual production is a bar with a diameter of 28mm and a length of 94mm, and the billet is heated to 950℃ and the die is heated to 300℃ before forging, and the imported graphite milk is used for lubrication to reduce the friction.

After the titanium alloy crank was forged and formed, the finished forgings are shown in Fig. 8.As can be seen from the figure, there is no underfilling, cracking, folding and other defects in the forging, and the forming quality is high, which meets the design requirements of the forging.

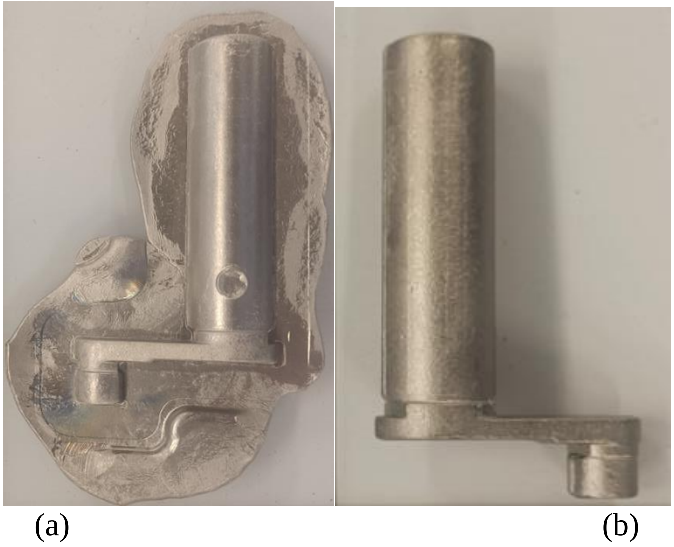

(a) (b)

Fig. 8 Finished crank forging (a) without trimming, (b) after trimming

5. Summary

This study focuses on the forging process of titanium alloy cranks, and high quality forming is achieved through structural analysis and process optimisation.Firstly, the advantages and disadvantages of longitudinal and transverse die splitting were compared with those of transverse die splitting for the structural characteristics of cranks with long shaft shape, thin ribs and small-angle connecting zones, and transverse die splitting was chosen to ensure the uniformity of performance.Secondly, the machining allowance and mould parameters are determined by calculating the shape complexity coefficient (S=0.285), the dimensions of the hot forgings are corrected by combining with the shrinkage coefficient, and the inverted flying edge groove is designed to balance the material flow and mould life.Numerical simulation verifies the feasibility of the process, with reasonable distribution of temperature and velocity fields and controllable forming load.In the actual production, 950℃ billet and 300℃ preheating mould are used, supplemented by graphite milk lubrication, and defect-free forgings are successfully obtained.The research results provide theoretical basis and practical reference for mould design and process optimization of complex titanium alloy forgings, and have significant engineering application value.

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