Numerical simulation and experimental trials on superplastic forming for thin-walled structure of Ti2AlNb alloy

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Keywords: Ti2AlNb Alloy, Superplastic Forming, Constitutive Equation, Numerical Simulation

Abstract. The difficult formability of Ti2AlNb alloy leads to the difficulty of traditional manufacturing methods to form the complex thin-walled components, limiting the wide application of Ti2AlNb alloy in aerospace. In this paper the superplastic forming process of Ti2AINb alloy with thin-walled structure was studied. The superplastic tensile tests of Ti2AINb alloy were carried out at varying temperature ranging from 920℃ to 980℃ and strain rate ranging from $0.001s^{-1}$ to $0.03s^{-1}$. The effect of the deformation-temperature and strain rate on the superplastic deformation behaviour was analysed, showing that the flow stress and elongation increase with the increasing temperature and the flow stress decreases, the elongation increases with the decrease of the strain rate. The elongation reaches the maximum value of 525% at the temperature of 940℃ and the strain rate of $0.001s^{-1}$. The constitutive equation taking into account the effect of strain was developed, which was implemented into the FE-based software Abaqus to simulate the superplastic forming of the thin-walled structure. The optimal values of the slab thickness and loading pressure-time curve were obtained by simulation and the superplastic forming tests of thin-walled structure were performed. The comparison between the numerical and experimental data with regard to thickness variation verified the accuracy of the finite element model. The research results provide a reference basis for the preparation of complex thin-walled structures of Ti2AINb alloy in aerospace.

Introduction

When hypersonic aircraft flies at high Mach speed, severe aerodynamic heating phenomenon may occur, resulting in a sharp rise in the surface temperature of the aircraft, which puts forward more stringent requirements for the material properties of components, especially for high-temperature structural materials with low density, high specific strength and good high-temperature performance[1-3]. Ti2AlNb alloy is a new Ti-Al intermetallic compound material type with an ordered orthogonal structure. It has excellent high-temperature properties (specific strength, specific stiffness, creep resistance at high temperatures, oxidation resistance, heat resistance and flame retardant properties). It can be used for a long time in the range of 600 ~ 750℃, and its density is lower than that of nickel-based superalloys. It has become an aerospace lightweight high-temperature structural material with the most potential to replace nickel-based superalloy [4-7].

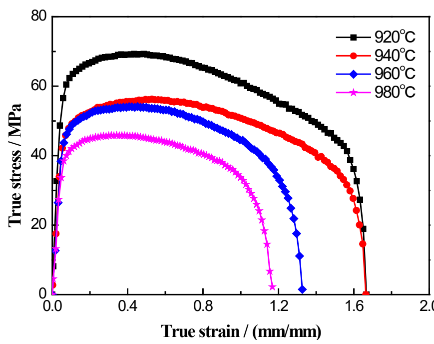
However, Ti2AlNb alloy is a refractory material with poor plasticity at room temperature, high deformation resistance at high temperature and demanding deformation conditions, which seriously restrict its development and industrial application. Superplastic forming technology is a process that takes advantage of the excellent formability of materials in the superplastic state to extend the materials under appropriate stress and strain rate by applying air pressure. This process is suitable for the forming of hard-to-deform materials, especially thin-walled and complex surface components [8-10].

In this paper, the superplastic deformation behavior of Ti2AlNb alloy was studied by high temperature superplastic tensile test, and the superplastic forming constitutive equation of the material was established. The numerical simulation of the superplastic forming process of the thin-walled structure of Ti2AlNb alloy was carried out by using the finite element software Abaqus to study the forming condition and the change of wall thickness to optimize the forming load. The pressure-time curve is obtained to provide theoretical guidance for the forming test of structural parts.

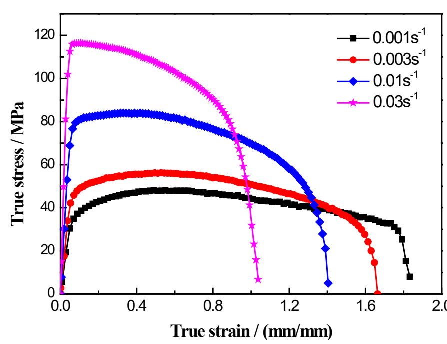
Establishment of constitutive equation

Superplastic deformation behavior

The experimental material is a 1.5mm thick Ti2AlNb alloy plate with a grain size of 11-12 grades and an average size of<8 μm. The high temperature superplastic tensile test was carried out on LETRYDL-20T electronic universal tensile test machine. The experimental deformation temperature was 920 ℃, 940 ℃, 960 ℃, 980 ℃ and the strain rate was 0.001 s^{-1}, 0.003 s^{-1}, 0.01 s^{-1}, 0.03 s^{-1}. The speed of the collet was kept constant during the stretching process. The obtained true stress-strain curves are shown in Fig. 1. At the same strain rate, the elongation and peak stress decrease with the increase of deformation temperature. The maximum elongation of Ti2AlNb alloy is 430 % at 920 ℃ and 0.003 s^{-1}. When the deformation temperature increases from 920 ℃ to 940 ℃, the superplastic elongation of Ti2AlNb alloy decreases from 430 % to 428 %, and the peak stress decreases from 69.3 MPa to 56.3 MPa. The elongation at 940℃ is not much different from that at 920 ℃, but the peak stress is reduced by 23 %.



(a) Under deformation temperatures



(b) Under different strain rates

Fig. 1 True stress-stain curves of Ti2AlNb alloy

At the same deformation temperature, the elongation decreases and the peak stress increases with the increase in strain rate. The maximum elongation of Ti2AlNb alloy is 525 % at 940 ℃ and 0.001 s^{-1}. When the strain rate increases from 0.001 s^{-1} to 0.03 s^{-1}, the superplastic elongation of Ti2AlNb alloy decreases from 525 % to 182 %. In contrast, the peak stress increases from 48 MPa to 116 MPa, indicating that the superplasticity of the material is sensitive to the change of strain rate.

Constitutive equation

The temperature during superplastic deformation is constant. Therefore, this paper temporarily ignores the influence of temperature and adopts the following Eq. (1) to describe the constitutive equation of materials:

$$\sigma = K\varepsilon^{n}\dot{\varepsilon}^{m} \quad (1)$$

Where: K is the strength coefficient; n is strain hardening index; m is the strain rate sensitivity index.

Logarithm of both sides of the above equation, we get:

$$\ln\sigma = \ln K + n\ln\varepsilon + m\ln\dot{\varepsilon} \tag{2}$$

Under specific strain, the m value is the slope of the lnσ-ln$\dot{\varepsilon}$ curve. True stress-strain curves of material at 940°C are selected to calculate the m values for different strains. The relationship between m values and strains is shown in Fig. 2. The m value decreases gradually with the increase of the strain, showing a linear relationship. Therefore, the expression of m value can be obtained by fitting it:

$$m = 0.334 - 0.155\varepsilon \tag{3}$$

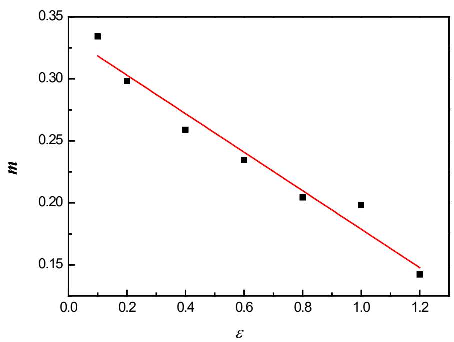


Fig. 2 m-ε curve

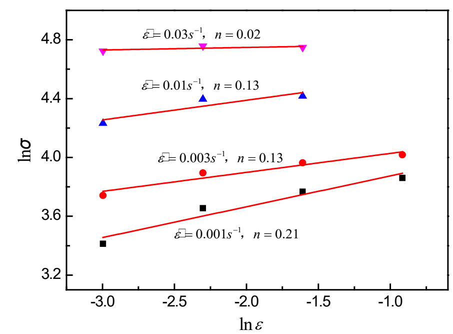


Fig. 3 lnσ-lnε curves

When the strain rate is constant, n is the slope of the lnσ-lnε curve from Eq. (2). The true stress-strain curves under different strain rates at 940°C show that when the strain is greater than 0.4, the stress gradually decreases with the increase of strain, and the dynamic softening plays a dominant role. Thus, n value can be calculated only from the strain value between 0.05 and 0.4, as shown in Fig. 3. Taking the average value of n calculated by different strain values, n = 0.1225 is obtained.

Substitute the calculated values of m and n into Eq. (2), and the following can be obtained:

$$\ln\sigma = \ln K + 0.1225\ln\varepsilon + (0.334 - 0.155\varepsilon)\ln\dot{\varepsilon} \tag{4}$$

The K values corresponding to different strains under four strain rates are calculated respectively. The results show that the K values under the same strain have little difference, that is, the K value is not sensitive to strain rate. Therefore, the K value at each strain is the average value of K calculated at the same strain at different strain rates. Draw K-ε curve, as shown in Fig. 4, and the expression of K is obtained by fitting the least square method:

$$K = 498.71 - 482\varepsilon + 123.70\varepsilon^2 \tag{5}$$

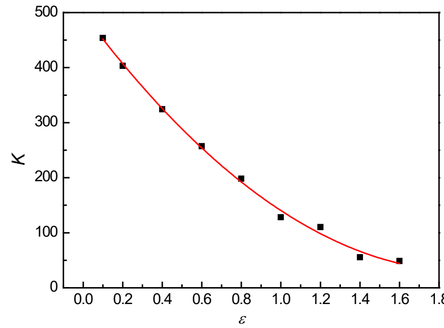


Fig. 4 K-ε curve

Therefore, the constitutive equation of superplastic formation of Ti2AlNb alloy at 940°C is obtained as follows:

$$\begin{cases} \sigma = K\varepsilon^n \dot{\varepsilon}^m \\ m = 0.334 - 0.155\varepsilon \\ K = 498.71 - 482\varepsilon + 123.70\varepsilon^2 \end{cases} \quad (6)$$

Where n = 0.1225. The experimental and computational results of flow stress is shown in Fig. 5 which indicates that the constitutive equation considering the effect of strain agrees well with the experimental data.

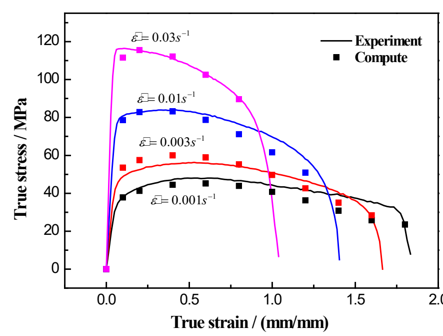


Fig. 5 Comparison of computational data (symbols) with experimental results (solid curves)

Establishment of finite element model of superplastic forming

FEM model

The finite element software Abaqus was used to simulate the superplastic bulging processes of of Ti2AlNb alloy thin-walled structural part. The dimension of the part is 300mm×300mm×15mm, and it is symmetrical, as shown in the Fig. 6. In order to simplify the calculation, only 1/4 of the member was taken for simulation, the plate size is 150mm×150mm, and the plate thickness is 1.5mm. The FEM model was established with Catia, and then imported into Abaqus software as shown in Fig.6. The plate was defined as shell elements and the die as discrete solid elements.

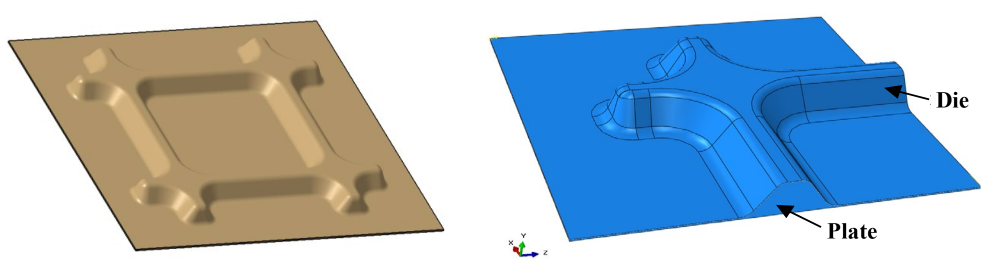


Fig. 6 Thin-walled structural part and FEM model

Material parameter setting

In the superplastic forming simulation of Abaqus software, the material properties can be defined through the Creep model, but the constitutive equation established in this paper is difficult to be converted into the creep constitutive model inherent in the software. Therefore, the Abaqus software needs to be redeveloped, and the superplastic constitutive equation established in this paper is written into the Creep user subroutine through Fortran programming language, so as to achieve accurate simulation of the superplastic forming process.

Pressure-time optimization control

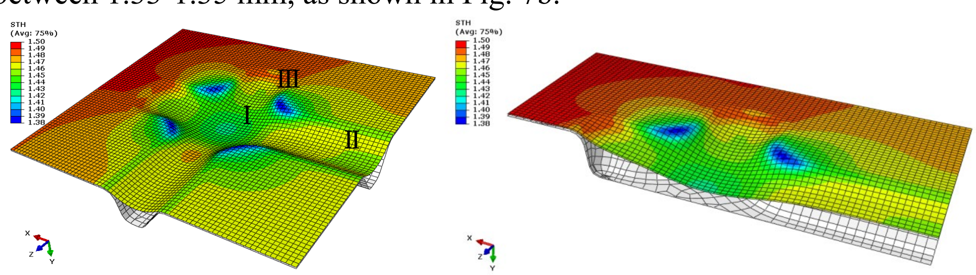
During the superplastic forming, properly controlling the pressure-time curve will make the maximum strain rate always near the target strain rate, which can not only shorten the forming time, but also reduce the uneven wall thickness. In Abaqus software, through load control algorithm, the solver will automatically adjust the loading of pressure in real time to ensure that the maximum strain rate is maintained near the target strain rate [11]. Abaqus software can automatically adjust the pressure during superplastic forming based on the maximum load and target strain rate set during the simulation.

In this paper, the maximum loads were set as 1.5 MPa, 2.0 MPa and 2.5 MPa respectively. According to the superplastic tensile test results of Ti2AlNb alloy, the target strain rate was set as 0.001 s^{-1}. The superplastic forming effects of Ti2AlNb alloy thin-walled structural parts under different loads were analyzed, and the optimal forming load parameters were obtained.

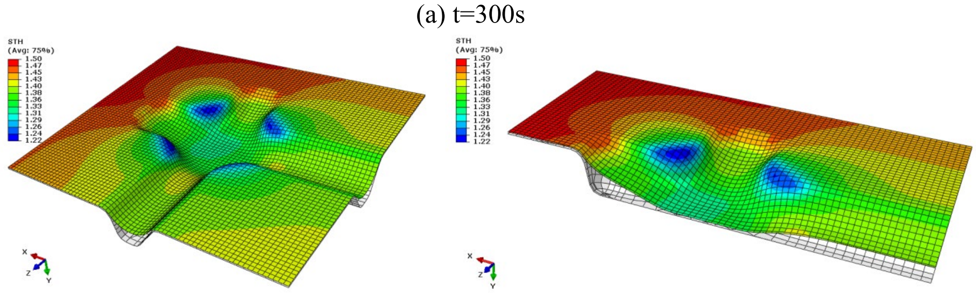
Simulation results and experimental verification

Simulation results of superplastic forming process

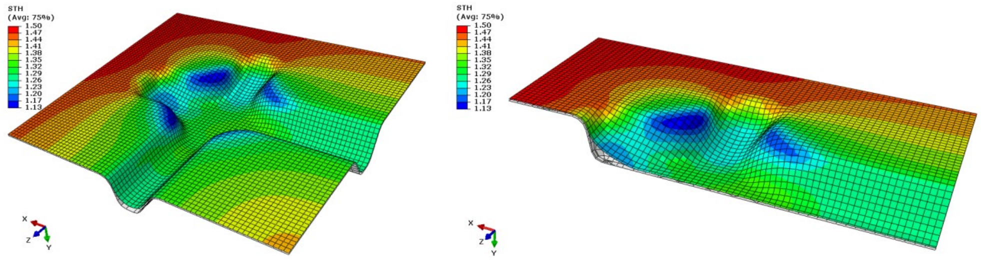
Fig. 7 shows the wall thickness distribution of Ti2AlNb alloy thin-walled structural part at different moments of superplastic forming under the pressure of 2.5 MPa. The superplastic forming of thin-walled structural parts can be divided into three parts, namely, plane zone I , bar zone II and fillet zone III. When the forming time is 300 s (Fig. 7a), the plate is in the free expanding state, and have not been in contact with the die, so the forming speed is faster, and the thinning of the plates is less. With the progress of deformation, the plate gradually contacts with the die. When the forming time is 600 s, the plane zone I of plate is completely contact with the die, and the thickness is distributed between 1.33-1.35 mm, as shown in Fig. 7b.



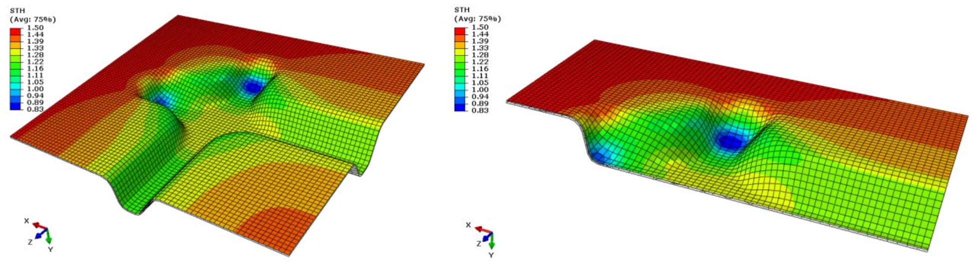
(a) t=300s



(b) t=600s



(c) t=900s



(d) t=1980s

Fig. 7 Superplastic forming process and wall thickness distribution of thin-walled structural part

When the forming time is 900 s, the bar zone II of plate is also fully attached to the die, and the thickness distribution is between 1.26-1.28 mm. The thickness of plane zone I is between 1.29-1.32mm. But the fillet zone III is still not attached, indicating that the round corner is not easy to form. At the time of 1980s, superplastic forming ended and the fillet zone III is fully pasted.

Due to the latest pasting, the plate has a large thinning, with a minimum wall thickness of about 0.83mm and a thinning rate of 44.7%. It can be predicted that when the thickness of the plate is small, cracking defects are most likely to occur here.

The pressure-time curve calculated automatically by Abaqus software according to the constant strain rate is shown in FIig. 8. This curve can provide a reference for the pressure loading of the subsequent thin-walled parts forming test, and realize the precise control of the superplastic forming process, so as to obtain the structural parts with uniform wall thickness distribution.

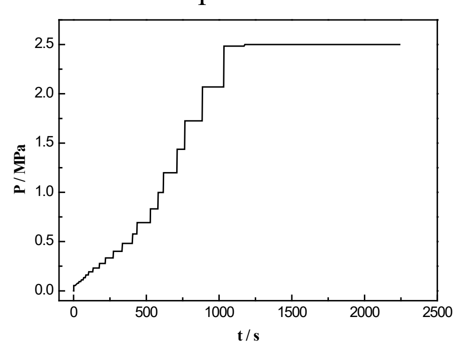
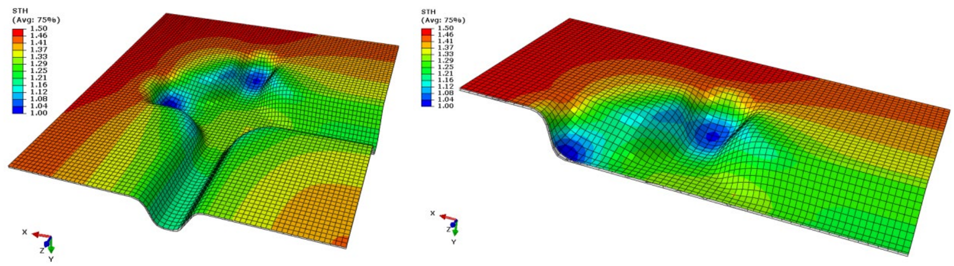


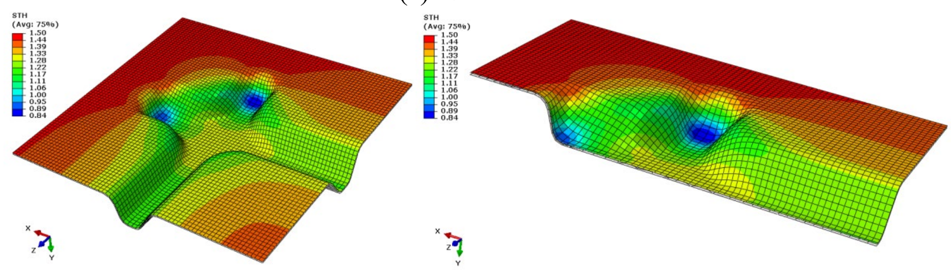
Fig. 8 Pressure-time curve

Influence of forming pressure on superplastic forming

Fig. 9 shows the wall thickness distribution nephogram of Ti2AlNb alloy thin-walled structural part under different pressures. When the pressure is less than 1.5 MPa, it can be seen from the profile that at the end of the simulation, the plate is not fully attached in the fillet zone III. While when the pressure is greater than 2.0 MPa, the plate is fully attached, and the superplastic forming is completed. When the pressure is 2.0 MPa and 2.5 MPa, the wall thickness distribution and thinning are basically the same.



(a) 1.5MPa



(b) 2.0MPa

Fig. 9 Wall thickness distribution of thin-walled structural part under different pressures

When the pressure is 2.0 MPa, the forming time of thin-walled structural part is 2520 s, which is 540 s longer than that when the pressure is 2.5 MPa. Therefore, with the increase of pressure, the superplastic forming time decreases. In order to shorten the forming time of parts, under the premise of not affecting the wall thickness distribution, 2.5 MPa is preferred to be formed.

Experimental study

The superplastic forming experiments of thin-walled structure was carried out at the temperature of 940 °C, strain rate of 0.001 s^{-1} and forming pressure of 2.5 MPa. The pressure-time curve obtained by finite element simulation was used for pressure loading. Fig. 10 shows the superplastic formed thin-walled structure of Ti2AlNb alloy. The part is well formed, and the rounded corners is completely pasted without cracking phenomenon.

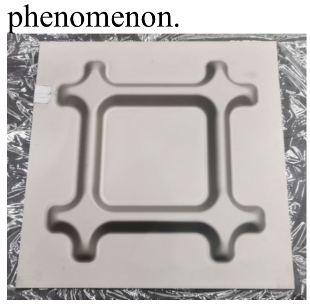


Fig. 10 Picture of the thin-walled structural part

The thickness of the bar area of thin-walled structural part ranges from 1.27 mm to 1.30 mm, and the wall thickness at the rounded corner is the thinnest, about 0.85 mm, which is basically consistent with the simulation results.

Summary

(1) At the same strain rate, the elongation and peak stress of Ti2AlNb alloy decrease with the increase of deformation temperature. With the increase of strain rate, the elongation decreases and the peak stress increases. When the deformation temperature is 940°C and strain rate is 0.001s^{-1}, the maximum elongation of Ti2AlNb alloy is 525%. The constitutive equation considering the strain factor was established.

(2) Using Abaqus software, the finite element numerical simulation of superplastic forming of Ti2AlNb alloy thin-walled structural part was carried out. As a result, the pressure-time curve was

obtained, and the pressure parameters were optimized. The wall thickness distribution was uniform and the forming time was short at 2.5MPa, which provided a theoretical basis for the selection of actual superplastic forming parameters.

(3) The forming expriment of Ti2AlNb alloy thin-walled structural part was carried out at the superplastic forming temperature of 940 °C and the maximum atmospheric pressure of 2.5 MPa. The wall thickness of the component was evenly distributed and no cracking phenomenon was found, which was basically consistent with the simulation results.

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