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Thermomechanical stress analysis of superplastic forming tools

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Abstract

A thermomechanical stress analysis of a superplastic forming (SPF) tool is performed by means of the finite element simulation of the whole forming process. The distributions of residual stress and distortion within the tool are investigated in order to evaluate the damage effects of thermomechanical loading. The effect of cyclic loading is related to the fact that residual stress and distortion in the tool accumulate as loading cycles proceed. The characteristics of the typical forming parameters of the sheet are described too. Meanwhile, the numerical simulation can be employed to compare various materials that can be used to manufacture forming tools.

Keywords: Superplastic forming process; Forming tools; Finite element simulation; Thermomechanical analysis

1. Introduction

The superplastic forming process is one of the most advanced manufacturing methods for producing highly complex thin-sheet components in a single operation. This process is widely used in aerospace industry. Superplastic forming (SPF) shows significant advantages as compared to conventional forming methods. Superplastic metals exhibit high ductility and very low resistance to deformation and are particularly suitable for forming processes that require very large deformation. Superplastic forming is usually completed within only one step and intermediate annealing is usually not necessary. This process allows the production of complex, deep-shaped parts with quite uniform thickness. Drawbacks of the process include the need of tight control of temperature and strain rate. Very long forming time makes this process impractical for high volume production series. In addition, the high cost of Ti–6Al–4V sheet metal [1] is a limiting factor for wide and generalized spreading of the technology. So, the majority of SPF production still remains in the aerospace, transport and architectural fields.

A typical cycle of superplastic forming process consists in the following sequences:

(I) the mould is heated up to the required temperature in the heating press, typically up to 900 °C for Ti–6Al–4V alloy;
(II) clamping pressure is applied on the boundary of sheet so as to clamp it with the mould whose surface forms a cavity of the required shape;
(III) gas pressure is applied to the opposite surface of the sheet, forcing it to gradually acquire the exact inner shape of the mould;
(IV) the mould is pulled out from the heating press for removing the formed component, and then pushed into the heating press again with a new sheet for forming a new component;
(V) the process from II to IV is repeated as many times as necessary to produce the required amount of components to be manufactured in one forming campaign;
(VI) after forming work, the mould is taken out and exposed to ambient air so that the temperature decreases gradually down to room temperature. The latter step is sometimes performed in the heating press to avoid any thermal shock.

A number of theoretical and numerical analyses have been performed for modeling superplastic forming. The contribution of numerical simulation is demonstrated clearly because industrial cases are very different from each other and require

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a particular attention [2]. Finite element simulation has been used extensively in the last few years to model SPF processes [3]. It has been shown to be a viable approach to model non-linear material behavior and contact friction phenomena, and it is beneficial to predict the deformation behavior especially for complex shapes. However, researches in the past mainly focused on the development of new advanced superplastic materials more than on the optimization of the technological aspects of the process, like the reduction of the forming time or the design of low cost forming tools. In particular, there has not been enough research on superplastic forming tools because they are generally considered as rigid body. Unfortunately, the current industrial growth of SPF for titanium alloy forming has been limited by the quality and durability problems of tools [4].

Tools are fundamental for the success of most manufacturing processes including superplastic forming processes. Satisfactory tools should be [5]: (i) accurate, able to continuously produce components at required dimensions and surface quality; (ii) durable, able to continuously operate at elevated temperature with no damage and to safely contain the gas pressure and the applied mechanical forces; (iii) productive, able to produce the highest output while controlling the pressure loading cycle to keep the maximum strain rate near the optimum value through the whole forming process and (iv) economical, able to manufacture components at minimum cost for optimized forming conditions.

Tool damage can be mainly attributed to one of the following causes [6]: type and quality of tool steels, design and manufacturing of the mould, surface treatment and heat treatment and effects of the forming process. In the case of SPF, the last factor includes three aspects:

(a) Permanent distortion: heating and cooling of tools will generate temperature gradients and thermal stress in tools. The thermal stress as well as the mechanical stress can result in creep deformation of the tools, leading to a lost of dimension and accuracy in the formed components. Furthermore, long-termed exposure at high temperature in aggressive environment may induce micro-structural changes in materials, which also result in detrimental evolution of the dimensions of tools [7].
(b) Cracking: initial micro-cracks can be caused by thermomechanical loading and cycling operation of tools. Macro-cracks will appear first in regions with high stress concentration [8]. This will be developed further in Section 2.2.
(c) Oxidation and oxide spallation: these phenomena can impair the surface of the mould, and thus alter the surface quality of the formed components [9,10].

In this paper, we have considered the superplastic forming of an axisymmetric box. The numerical simulation of the mould and sheet is performed thermomechanically for the whole superplastic forming process. The distribution of residual stress and deformation of the mould are investigated in order to analyze the damage effects of the thermomechanical loading on the mould. The finality of the research is to enhance the quality of tools and increase their service lifetime.

2. Materials and finite element modeling

2.1. Presentation of materials

Selection of tool materials includes consideration on both the mechanical properties and the oxidation resistance. Ni–Cr–Fe high-alloyed heat resistant cast steels are commonly used to manufacture superplastic forming tools for titanium alloys sheets. Other materials, such as reinforced concretes or ceramics, are still under investigation [11]. Heat resistant cast steels, either austenitic or ferritic, show satisfactory performance as their high chromium content ensures a good resistance to oxidation damage, and the addition of nickel and carbide elements provides rather high strength at high temperature. Table 1 shows the chemical composition of the superplastic tool material investigated in the paper.

The density of the material is 8200 kg/m^3 and the Poisson ratio is 0.29. Other related parameters vary with temperature as indicated in Fig. 1 where the experimental data are plotted. The units of these parameters are as follows: Young's modulus E is MPa; thermal expansion ε is 1/K; thermal conductivity k is J/(m s K) and specific heat c_p is J/(kg K).

Rate-dependent plasticity is the constitutive relation of the mould and the sheet. The power-law creep model is attractive for its simplicity. It is defined by the equivalent uniaxial behavior for modeling steady state creep. As the stress state remains essentially constant, the time-hardening form is used here:

$$\bar{\dot{\varepsilon}}^{\mathrm{cr}}_{\mathrm{eq}} = A\tilde{\sigma}^n t^m \quad (1)$$

where $\bar{\dot{\varepsilon}}^{\mathrm{cr}}_{\mathrm{eq}}$ is the uniaxial equivalent creep strain rate; $\sqrt{\frac{2}{3}\dot{\varepsilon}^{\mathrm{cr}} : \dot{\varepsilon}^{\mathrm{cr}}}$; $\tilde{\sigma}$ the uniaxial equivalent deviatoric stress (for isotropic case, it is Mises equivalent stress); t the total time (in second) and A, n, m are the constant parameters that are functions of temperature.

For physically reasonable behavior, A and n must be positive and $-1 < m \leq 0$. Their values are listed in Table 2. Obviously, the creep law varies with temperature because

Table 1
Chemical composition of the tools investigated (wt%)

Material name	GX45NiCr49_27
Fe	Balance
C	0.458
Si	1.21
Mn	0.98
S	0.001
P	0.008
Ni	49
Cr	26.76
W	4.95