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Research Article

Simulation of the Blow-Up and Cooling Processes of Hollow Blade Manufacturing

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Abstract

The results of numerical simulation of hollow blade blow-up of a superplastic material and its subsequent cooling during the manufacturing process are presented. For each stage of the process, the distribution of internal strains and stresses are calculated to assess the effect of process parameters on the final result.

Keywords: Hollow blade, superplasticity, cooling processes, Deform3D

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1. Introduction

The history of the hollow blades for GTE begins in 1940 when the German companies BMW and Junkers developed cooling systems for blades of the 109-004 and 109-003 turbojet engines [1]. The hollow blades were fabricated by deep-drawing (made of Tinidur) and welding the resulting one-sheet design along the trailing edge (made of Cromadur). Using this method to manufacture hollow blades savings in nickel alloys were made, which were in short supply during the war. The operation had the added advantage of significantly reducing the operating blade temperature and therefore increasing their life. At the same time, attempts to manufacture hollow blades for compressors were not successful.

The modern hollow blade of a compressor is a multi-sheet structure with complex geometry, which is designed for significant aerodynamic and mechanical loads. Manufacture of these is made by welding, stamping and pneumatic forming. Individual elements of the hollow blades, especially the power set, undergo of significant deformation during production, so the process of shaping the blades is taking place in the superplasticity state [2,3] of the material used. An example of this complex structure is a hollow blade of the fan of the Trent-1000 engine, which is more than one meter length.

The temperature range of superplastic behavior of titanium alloys is very narrow (usually 875-925°C [4]), which complicates the superplastic forming of large products as it places high demands on the equipment used.

One of the mechanisms responsible for superplasticity is grain boundary sliding which makes the material behave like being in an environment of hard balls, as if placed in a non-Newtonian viscous lubricant (where flow stress depends on the strain rate). The contribution of this mechanism to the nature of the flow is estimated to be 50%. Therefore, the main mathematical model of superplastic material behavior is the power law [5]

$$\sigma = c\varepsilon^{n}\dot{\varepsilon}^{m} + y \qquad (1)$$

where σ – internal stresses, ε – strain value, n – strain hardening factor, m – strain rate hardening factor, values of constants c and y are determined by alloy properties.

The main disadvantage of the power law model is the narrowness of the applicable range of strain rates, which limits its use. Another problem is the complex nature of hardening, which is also appears as well.

It is clear that the experimental measurement of flow curves is a time consuming process, where the shape of these curves depends on experimental conditions (strain rate, temperature). It is therefore sensible to use tabular material flow curves in numerical modeling.

2. Blow-up process simulation

The hollow blade workpieces are sometimes welded from titanium alloy sheets, but more frequently diffusion bonding is used, while other methods (like argon arc-welding) are used infrequently. After joining the welded workpiece is exposed of swirling to form the desired shape (for fan blades a swirl angle can reach 90 degrees). The swirled workpiece is set into mold and then placed into an oven to be heated to superplastic temperature. Then hot inert gas (usually argon) is fed through a pilofacturing hole at the tail of the blade under high pressure which causes the blowing up of the blade, which in turn fills the mold completely.

The quality of the product is determined by pressure curve followed during the blow-up process [6, 7]. It should be chosen based on the strain rate encountered and must not exceed the boundary values for the superplastic state.

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This work focuses on the blowing up of a whole blade of Ti-6Al-4V, which is applied to the inner part of the blade between the sheets. Modeling of this process was done using the software package Deform 3D v.10.

As the larger part of the blade has a cellular structure with walls of given thickness which does not changes along the vertical axis of the blade, then to reduce calculation time only specific segments of the blade with cut-off planes perpendicular to the vertical axis of symmetry of the blade were used for calculations. There are planes of symmetry on both sides of the clipped segment, with sticking conditions at the boundary points of the mold. The function of the pressure changing at the boundary of the scapula were chosen as the boundary conditions.

As the process is isothermal (at temperature 925°C) and the elastic properties of the alloy at the chosen temperature were scarce, then only plastic behavior of the alloy was taken into account. The numerical model mesh consists of 160,000 tetrahedral elements.

The pressure curve (see Fig.1) was determined from a number of numerical experiments where the strain rate was limited to be below $5 \cdot 10^{-3}$ 1/sec. When the mold was almost filled, pressure was increased and at the end of the process it had reached 6 MPa.

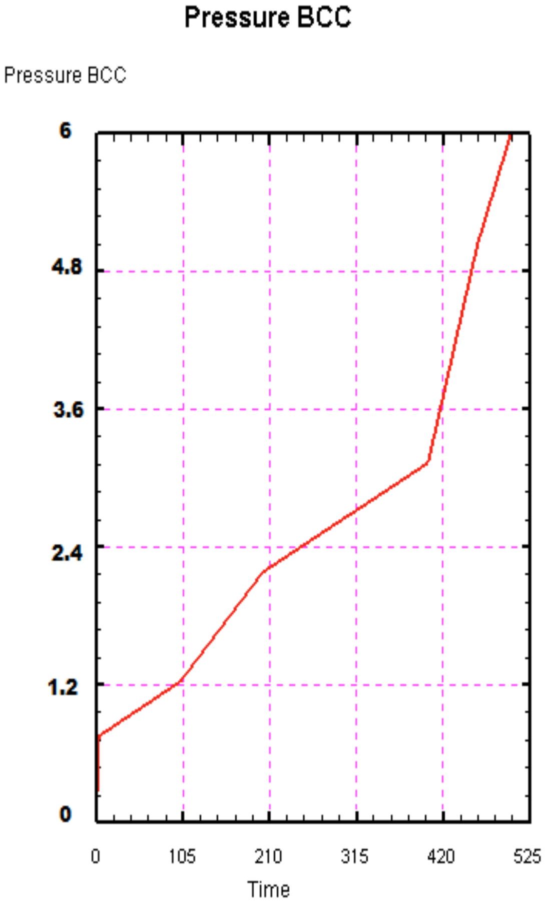


Fig. 1. The pressure curve for blow-up process.

Among the most difficult to measure parameters of the blow-up process is the coefficient of friction (μ) between blade sheets and the mold. In the present model it was decided to vary the value of μ between 0 and 0.8 to investigate its effects on filling the mold.

To determine the sensitivity of the process to plastic flow parameters, it was decided to vary the power factor of strain hardening (n) between 0 and 0.4 in increments of 0.1 at a constant coefficient of friction of 0.4. This was decided as the curves of superplastic flow for different titanium alloys [5, 8] as well as for different strain rates can vary substantially pointing to the requirement of accurate material data.

Tab. 1 represents value of parameters, that were used for these numerical experiments.

Table 1. Set of parameters of numerical experiments.

μ	0.0	0.4	0.8	0.4	0.4	0.4
n	0.0	0.0	0.0	0.2	0.3	0.4

Figure 2 shows the changing shape of the blade during the blow-up process. At the beginning, the blade is made of two sheets which were welded along the edges and at few points inside the plate surface. With increasing gas pressure the free (not welded) parts of the sheets start to move till they touch the walls of the mold. It can be seen that the biggest strains appear on the inner chords, which form the ribs of the hollow blade.

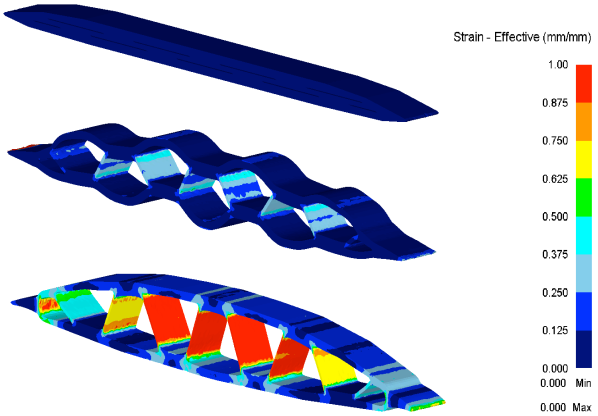
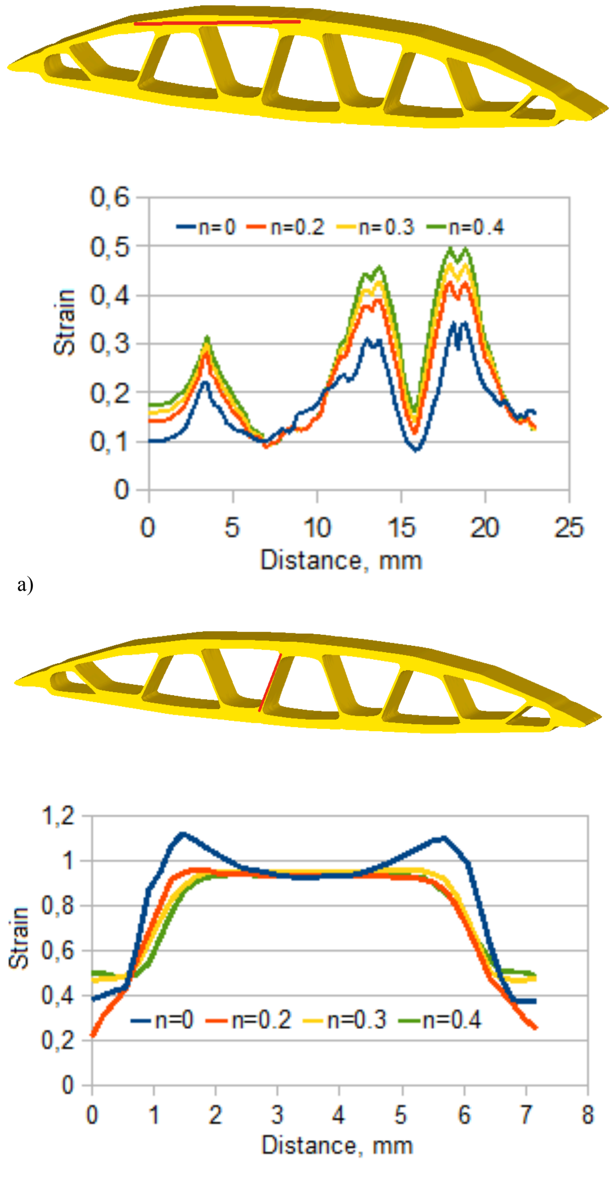


Fig.2. The shape of the hollow blade at different stages of the blow-up process.

The results of changing the power hardening coefficient demonstrate (see Figure 3) its significant effect on the strain distribution along the blade.

When there is no strain hardening (n=0), strain is concentrated within the inner chords. Strain distribution is non-homogeneous with the maximum of strain located near the joints of the chords with the blade sheets. This causes uneven thickness of the chord where the chord center is thicker than the ends.

By increasing the coefficient of strain hardening the points of joining of the outer sheets of the blade with the inner chords deform more than in the previous case (see Figure 3a). Distribution of the strain within chords is more uniform (see Figure 3b).



a)

b)

Fig. 3. Strain distribution along the outer sheet (a) and along one of chords (b) for different coefficients of strain hardening

In addition, a geometric distortion of the hollow blade appears as inner chords, that form an inner ridged structure, shifts at about 0.5% of the blade width.

Strain hardening assists the filling of the mold by increasing *n* the gap between the outer sheet and the mold at the points of joining the sheet and chords diminishes.

Thus numerical simulations show that to form the inner ridged structure with a uniform thickness and a uniform filling of the mold, the process should take place under conditions corresponding to the boundary of the zone of superplastic flow material behaviour.

The variation of friction coefficient shows very little quantitative change in the distribution of strain both for large $\mu = 0.8$ and for the absence of friction ($\mu = 0$). It should be noted that in reality, at the operating temperatures friction is minimal so it can be ignored.

At the same time, calculations shows that increasing the coefficient of friction reduces the speed of filling the mold at points of the chords and the outer sheets joints, which can affect the time required to complete the process, but the value of the distortion is minimal and for given geometry is 0.1 mm. It is expected that for isothermal forging (twisting of the blade) the effect of the friction coefficient will significant as during twisting the workpiece slides on the entire surface of the mold.

3. Hollow blade cooling

The numerical simulation of cooling the GTE hollow blades after their manufacture is necessary to determine the optimal regime to minimize residual stresses and strains. The direct cooling with on air causes high residual stresses and blade warpage (numerical calculations in DEFORM 3D show deformations to be about 5%). Cooling at the furnace although optimal in terms of a producing a less steep temperature gradient, it is inefficient in terms of production because of the duration of the process and tear and wear of equipment. It is required to select the appropriate cooling regime for which deformations and residual stresses are not large while the duration of the process and the cost of using the necessary equipment are minimal.

The process of cooling the hollow blades for three different regimes of cooling: on air, with a single temperature step, and with two temperature steps were simulated. In all cases, the boundary conditions were set to convective heat losses with a coefficient of 20 W/°C•m^2. The saddle of the blade is sandwiched between two solid supporting blocks (see Figure 4). To improve the convergence of the calculation at a few select points a sticking condition was set. A computer model of the cooling process takes in account elastoplastic material properties and thermal conductivity of the alloy VT6 (Russian equivalent of Ti-6Al-4V) [9, 10].

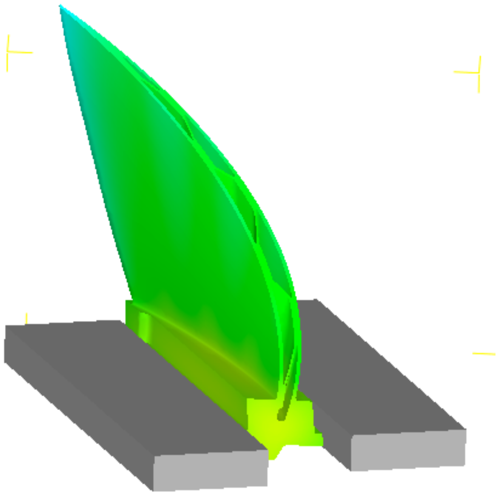


Fig.4. General view on the clamp (blade is shown sectioned).

When cooled in open air, there are some points of the hollow blade where the strain reached is 2%, which significantly distorts its geometry (as the twist angle increases by one degree).

Slower cooling in an oven produces very small strains (less than one percent) and residual stresses of 10 MPa, which points to the ideal mode of cooling, in an oven.

For production purposes, the optimum cooling is to cool at incubator. There were two cases studied : with one incubator at a temperature of 500 degrees, and with two incubators with temperatures of 600 and 300 degrees, respectively. Using a incubator allows to reduce temperature gradients, and, as a consequence to reduce residual strains and stresses. These cases take into account short-term stay on open air simulating the transfer of the blade from the oven to a incubator and between incubators as it happens in production. The curve of temperature changing with time for different regimes is shown in Figure 5.

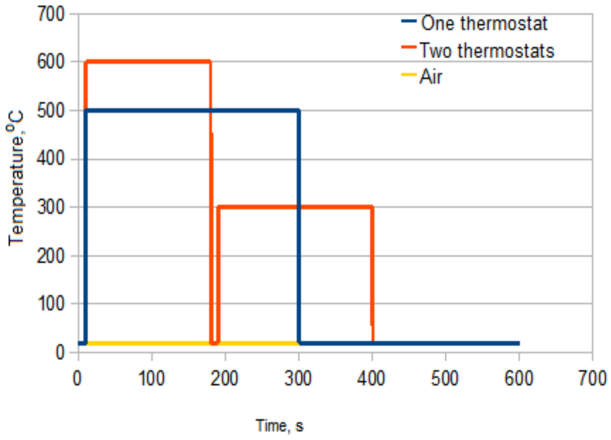


Fig.5. Change of temperature with time for the different cases of hollow blade coolings.

Following calculations results were obtained for temperature and stresses (see Figure 7) for the points shown in Figure 6.

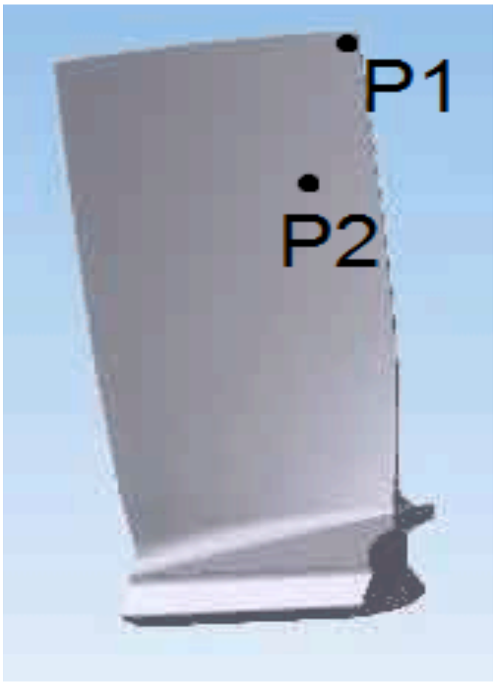


Fig. 6. Points on the blade surface where temperatures and stresses were measured.

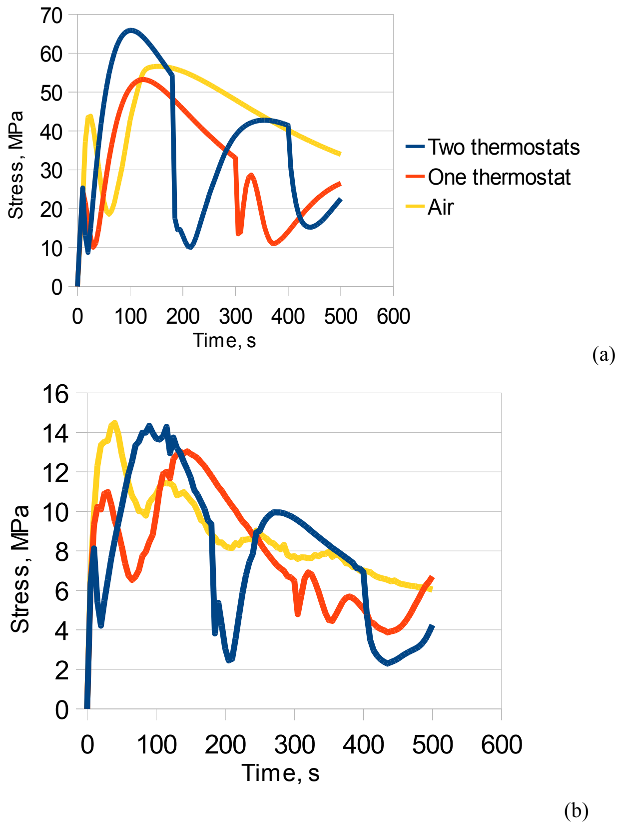


Fig.7. Change of stress with time for different cases of the hollow blade cooling process at points P2 (a) and P1 (b).

Point P1 is located on the edge of the blade far from the saddle and point P2 is located at the junction of the inner chord with the outer sheet of the blade. The maximum value of the internal stress is achieved at this point as calculations show.

From the analysis of the graphs it is can be seen that:

- Using incubators allows to reduce the residual stresses due to cooling in the hollow blades.
- Comparison of the residual stresses for the two cooling cases shows that using a two-stage scheme is not valuable as residual stresses are about the same.

The actual process of blade cooling has a significantly uneven character as convective heat transfer depends on the geometry of the blade and the geometry of the base on which it is resting. Preliminary calculations with the StarCCM package for a simple geometry blade show decreasing of the heat at the bottom part of the blades for 15-30%, which may be caused presence of the base that restricts limits the free flow of air. This can produce temperature differences between the upper and lower sheets of blades of up to 150 degrees, as sheets are connected only by thin parts with a limited heat flux capability.

The next step in this project will be the simulation of the hollow blade cooling on the base with taking in account gas dynamics, thermal and elastic processes all together.

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