Computer simulation of superplastic forming of a three-sheet structure containing an ultrafine-grained core

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Abstract. Superplastic forming of a three-sheet structure is considered. The focus is on overcoming the main disadvantages of the process of manufacturing of such structures by means of the SPF/DB technique including high temperatures of treatment and the formation of folds on the outer surface of the article manufactured. The application of ultrafine-grained sheets of titanium alloy Ti-6Al-4V has been analyzed in order to avoid these disadvantages. Various combinations of the use of ultrafine-grained and microcrystalline sheets as skin and core sheets are considered by means of the finite element analysis. The standard power law of superplasticity is used for analysis with material constants determined from technological experiments. The conclusion is made that the most attractive way appears to be the usage of ultrafine-grained material for the core sheet and microcrystalline material for the skin sheets.

1. Introduction
Modern aerospace industry deals with articles that combine high specific strength and reliability. Such requirements are met by three-layer structures with corrugated filler, obtained by superplastic forming (SPF), concurrent with diffusion bonding (DB) of titanium alloys [1]. The scheme of this process was published in many works [2-5]. Briefly, it should be noted that the structure forms a package of three sheets. Two sheets serve as shells. The inner sheet is selectively connected to the skin by means of DB. In the SPF process, the inner sheet is stretched between the skins. As a result, the face sheets take the form of a die, while the core sheet forms stiffeners.

It should be noted that interest in three-layer structures still does not disappear. The key detail of the 5th generation aircraft engine – a hollow fan blade – has a similar design. For the first time the English company Rolls-Royce began to produce hollow blades for aircraft engines of the new generation. Now hollow fan blades are developed by the French company Snecma and others. The unique face plates of golf club heads also are three-layered [6].

Along with the development of the use of three-layer corrugated structures manufactured by the SPF/DB technique, the problems of their quality and production efficiency continue to be essential. The main of them are as follows:
- high temperatures of treatment 900–925 °C [1];
- oxidation during superplastic forming leads to the formation of the so-called α-layer on the surface of the article, which must then be removed by chemical etching;
- low resistance of the tools made of expensive heat-resistant materials;
- formation of folds on the surface of the product.

Solving the above problems, a filler sheet made of the ultrafine-grained (UFG) titanium alloy can be produced, while the face sheets can be made of rolled sheets having a microcrystalline (MC) structure [7, 8]. The domestic corporation VSMPO-AVISMA has experience in manufacturing commercial sheets with a grain size of less than 1 µm.

The purpose of this study is to show the possibility of solving these problems on the basis of the results of modeling and experimental data.

2. Materials and methods

Figure 1 shows a scheme of a fragment of a three-sheet structure. All three sheets are the commercial titanium alloy VT6 (Ti-6Al-4V). Skin sheets with a thickness of $s_s$ have an MC structure with an average grain size of 3 µm. The core sheet with a thickness of $s_c$ possesses an UFG structure with an average grain size of 1 µm. The pressure $p$ from the inertia gas is applied to the free surfaces of the inner cavities of the sheet package. The height of the structure $H$ is equal to the maximum distance between the plates of the die. The angle between the ribs and the skin is denoting as $\phi$. The temperature of SPF is equal to 750 °С.

\[ \sigma = K \xi^m \quad \text{or} \quad \xi = C \sigma^n, \]

where $\sigma$ is the flow stress, $\xi$ is the strain rate; $K$, $m$, $C$, and $n$ are the material constants to be determined experimentally. To determine the values of material constants for UFG titanium sheets, technological experiments with constant pressure have been done in accordance with the procedures described in details in [9]. The obtained results are collected in table 1.

| $T_{SPF}$, [°C] | $p$, [MPa] | $t$, [s] | $H$, [mm] | $R$, [mm] | $r_0$, [mm] | $s_0$, [mm] | Average grain size, µm |
|-----------------|------------|----------|-----------|-----------|-------------|-------------|------------------------|
| 750             | 2.0        | 1000     | 35        | 35        | 1           | 1           | ~1                     |
| 2.5             | 470        |           |           |           |             |             |                        |
| 3.0             | 305        |           |           |           |             |             |                        |

To describe the mechanical behavior of the VT6 sheet alloy with the UFG structure, the following pair of experimental data was treated in accordance with procedures described in [9]: the duration of forming under a constant pressure of 2.5 and 3.0 MPa equals to 470 and 305 s respectively. As a
result, it was found that \( m = 0.4216 \) and \( K = 1181 \text{ MPa·s}^m \). This set of material constants was used in calculations to describe the mechanical response of the UFG material. The constant pressure generated under relatively low pressure resulted in the fact that considerable grain growth influenced the mechanical response of the material under study. Therefore, to describe the rheological behavior of the MC sheet alloy, the following pair was chosen: the duration of forming under a constant pressure of 2.0 and 3.0 MPa equals to 1000 and 470 s respectively. The values of the determined material constants were be as follows: \( m = 0.2955 \) and \( K = 531 \text{ MPa·s}^m \). This set of material constants was used in calculations to describe the mechanical response of the MC material.

The formulation of a boundary value problem in the mechanics of solids is described in details in [10]. Standard ANSYS software was used to solve it. The calculation area was divided into 397 PLANE82 elements with the Plane strain option. The tool was set as an absolutely rigid body using the TARGE169 element. The boundary conditions at the interface between the tool and the deformable body were set by the contact element CONTA172.

The following numerical data were chosen for the calculations: \( s_s = 1.6 \text{ mm}, s_c = 0.8 \text{ mm}, H = 10 \text{ mm}, \phi = 60^\circ \). Computer modeling was carried out in a two-dimensional setting by using the software ANSYS10.0 (ED). In view of a symmetry, only half of the represented fragment was considered. The finite element mesh is shown in figure 2.

![Finite element mesh at the initial position.](image)

The regime of loading (pressure time cycle) has been chosen as follows: at the first stage of forming, the pressure is increased linearly with time up to its maximum value \( p_{\text{max}} \) to ensure optimum conditions for superplasticity [11]. At this stage, the core sheet is deformed under conditions of superplasticity, stiffening ribs are formed. The first stage continues until the skin sections joined to the core touch the surface of the die. The second stage proceeds under conditions of creep up to smoothing the outer folds.

Four different combinations of microstructures of skin and core sheets and regimes of loading have been considered as listed in table 2.

| No. | Layer’s thicknesses and microstructures | Duration of forming, \( s / p_{\text{max}} \), [MPa] | Holding time, \( s \), under constant \( p_{\text{max}} = 4 \text{ [MPa]} \) | Depth of the groove, [mm] | Equivalent strain of the core (max) |
|-----|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------|----------------------------------|
| 1   | 1.6+0.8+1.6 UFG+UFG+UFG             | 900/2                                | 7200                                 | 0.11                           | 1.446                            |
| 2   | 1.6+0.8+1.6 UFG+UFG+UFG             | 3600/4                               | 7200                                 | None                           | 1.459                            |
| 3   | 1.6+0.8+1.6 MC+UFG+MC               | 900/2                                | 7200                                 | 0.12                           | 1.193                            |
| 4   | 1.6+0.8+1.6 MC+UFG+MC               | 3600/4                               | 7200                                 | None                           | 1.308                            |

The results of calculations for all the considered variants show that if the value of the angle of inclination of the stiffeners to the skin does not exceed 60\(^\circ\), the thickness of the skin sheet should be at
least twice as thick as the core sheet. The parameters that control the wrinkle smoothing process are the holding time (which is quite obvious) and the time of forming. When forming according to the law of linear pressure, an increase in time of forming leads to the decrease in the strain rate. As seen in figure 3, the most favorable situation is associated with the regime of loading up to $p_{\text{max}}=4$ MPa for 1 hour and consequent holding under this pressure for 2 hours.

![Figure 3](image)

**Figure 3.** Distributions of the first principal creep strain calculated for variants 3 (a) and 4 (b).

4. Conclusions

The durability of the figured dies increases significantly with decreasing temperature, which is important for the stability of the product dimensions. As the simulation results show, the problem of folds is solved both in the UFG+UFG+UFG circuit (Variant 2) and in the MC+UFG+MC circuit (Variant 4). Taking into account the cost of the UFG material, the MC+UFG+MC circuit design is clearly preferable. The relatively long duration of the SPF reduces the efficiency of the process as the productivity of the process decreases. The problem of folds could be solved using skin sheets with a large grain size, thereby reducing the exposure time. However, this technique will cause a problem during welding and will not lower the temperature of the process that reduces the structural strength. Thus, the use of the UFG material as a core sheet in a three-layer structure makes the SPF/DB process economically attractive.

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