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# Investigation on the thickness distribution of highly customized titanium biomedical implants manufactured by superplastic forming

D. Sorgente[a], G. Palumbo[b,*], A. Piccininni[b], P. Guglielmi[b], S.A. Aksenov[c]

[a] Università degli Studi della Basilicata, School of Engineering, Viale dell'Ateneo Lucano 10, 85100 Potenza, Italy
[b] Politecnico di Bari, Department of Mechanics, Mathematics and Management, Viale Japigia 182, 70126 Bari, Italy
[c] National Research University "Higher School of Economics", Tallinskaya 34, 123458 Moscow, Russia

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ABSTRACT

Mechanical performances of titanium biomedical implants manufactured by superplastic forming are strongly related to the process parameters: the thickness distribution along the formed sheet has a key role in the evaluation of post-forming characteristics of the prosthesis. In this work, a finite element model able to reliably predict the thickness distribution after the superplastic forming operation was developed and validated in a case study. The material model was built for the investigated titanium alloy (Ti6Al4V-ELI) upon results achieved through free inflation tests in different pressure regimes. Thus, a strain and strain rate dependent material behaviour was implemented in the numerical model. It was found that, especially for relatively low strain rates, the strain rate sensitivity index of the investigated titanium alloy significantly decreases during the deformation process. Results on the case study highlighted that the strain rate has a strong influence on the thickness profile, both on its minimum value and on the position in which such a minimum is found.



## Introduction

Applications of titanium (Ti) alloys in the manufacturing of complex shaped parts by Super Plastic Forming (SPF) cover a very large range of engineering fields. Beside aerospace, which is the one with the largest historical background [1], the manufacturing of Ti biomedical implants is certainly an interesting application of SPF for cranial and maxillofacial prostheses [2] and for the production of cardiovascular pacemaker [3]. For the production of biomedical prostheses, the cycle time needed for the forming process is commonly seen as a secondary aspect since a single-piece batch has to be manufactured. While this can be true from an economic point of view, the reduction of the forming time can be considered beneficial for the post-forming performance of the material, since it reduces the material degradation, both on its surface and in the substrate, due to the oxygen contamination [4] and to the grain growth [5], both related to the exposure time at elevated temperatures [6]. On the other hand, at strain rates higher than the optimal value (with consequent shorter forming times), a less uniform thickness distribution corresponds due to the decrease in the strain rate sensitivity index *m* [7]. Nevertheless, during the forming operation an optimal strain rate is chosen for a datum application, but, due to the complex shape of the die, the material undergoes very different strain rates in different areas of the blank. In this context, the need for a reliable material model, able to predict its behaviour in a wide range of strain rates, is beyond doubt. Numerical simulation based on the finite element (FE) method had been largely adopted in the manufacturing of biomedical implants [8] also for the prediction of microstructural evolution in Ti alloys [9].

Since the numerical approach is an unavoidable step to properly design the SPF process, the choice of the most suitable constitutive equation to correctly describe the superplastic behaviour of the alloy under investigation becomes a key factor. The model proposed by Backofen [10–15], relating the equivalent stress to the equivalent strain rate by means of the two constants *C* (the strength coefficient) and *m* (the strain rate sensitivity index), as well as the improved formulation including the effect of the strain hardening proposed by Ludwig [16] are widely adopted in several studies available in literature. On the other hand, the research for augmented constitutive equations taking into account mean grain size, the microstructural evolution [17,18], and the fraction of voids [19] is still an open issue. In the SPF process, since the material is clamped at elevated temperatures between a die and a blank-holder, almost no drawing occurs in the die cavity. Thus, the thickness distribution of the SPFed sheet is strongly related to the material behaviour and, in turn, to process parameters.

* Corresponding author.
*E-mail address:* gianfranco.palumbo@poliba.it (G. Palumbo).

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In this work, with the aim of creating a reliable tool for the prediction of the thickness distribution of SPFed biomedical implants, a numerical model is proposed providing an improved material modelling based on the Backofen formulation. Material constants are implemented as strain and strain rate dependent, thus locally providing a more accurate description of the material behaviour since different regions of the blank experience different strain and strain rate levels during the forming operation. Such an approach was implemented and subsequently validated by experimental trials on the Ti6Al4V-ELI Ti alloy. Material constants derived from free inflation tests have demonstrated to lead to a more accurate prediction of the material behaviour if compared to ones derived by tensile tests [20]. Starting with this assumption, free inflation tests were carried out in order to build a suitable material model to be implemented in FE simulations of the SPF process of a cranial prosthesis chosen as case study. A simulation plan was run to analyse the effect of strain rate on the thickness distribution. Experimental trials were then performed for two chosen values of the strain rates to validate numerical results.

## Material and methods

### *The investigated titanium alloy*

For both the material characterization and the manufacturing of the biomedical prosthesis by SPF, the Extra Low Interstitial Titanium alloy Ti6Al4V-ELI (thickness: 1 mm) was used. The investigated material was purchased in the annealed condition (790 °C for 68 min and then air cooled). Its chemical composition is reported in Table 1.

### *Free inflation tests for material characterization*

Free inflation tests were run at 850 °C. The test temperature was chosen according to results achieved by Lee et al. [21] on the same Ti alloy. With the aim of modelling the material behaviour in a sufficiently large range of strain rate values, the following six different pressure regimes were adopted: 0.25–0.50, 0.50–0.75, 0.75–1.00, 1.00–1.25, 1.25–1.50, 1.50–1.75 MPa. Each regime was characterised by two different pressure values between which the Argon gas pressure was repetitively changed with several pressure jumps according to an evenly spaced time series. These jumps allowed to include, in a single test, information about a material response that is strictly related to the strain rate sensitivity index. Nevertheless, each pressure regime corresponded to a mean value of the strain rate that the material experienced during the test. The gas pressure was regulated by an electronic closed-loop proportional valve (maximum pressure 2 MPa) and the dome height was continuously acquired by a magnetostrictive position transducer (maximum stroke 50 mm). All the tests were stopped at a constant dome height value of 25.5 mm which, considering a die cavity radius of 22.5 mm and an entry radius of 3 mm, geometrically corresponds to a semi-spherical condition of the inflated sheet [22]. After the test, the inflated specimens were sectioned along the meridian direction and the final thickness was measured at the dome apex by means of a digital calliper. Further details about the equipment and the pressure jump methodology on this Ti alloy can be found in [23].

**Table 1**
Chemical composition of the investigated Ti alloys.

| Al% | V% | Fe% | C% | N% | H% | O% | Ti% |
|---|---|---|---|---|---|---|---|
| 5.88 | 3.87 | 0.14 | 0.22 | 0.006 | 0.002 | 0.112 | Bal. |

### *Material modelling*

The results of free inflation tests described in the sub-section "Free inflation tests for material characterization" were processed in order to characterize the material behaviour. In each test, the measured values of pressure $P_i$ and dome height $H_i$ for every instant of time $t_i$ as well as the final thickness $s_f$ were recorded. The value of thickness $s_i$ corresponding to the current dome height $H_i$ was calculated as:

$$s_i = s_0 - (s_0 - s_f)\frac{2H_i^2}{H_i^2 + (R_0 + \rho_0)^2} \quad (1)$$

where $s_0$ is the initial specimen thickness, $R_0$ and $\rho_0$ are the die cavity radius and the entry radius, respectively. The values of the effective strain, effective strain rate and the effective stress were calculated as:

$$\dot{\varepsilon}_i = \frac{\ln(s_i/s_{i+1})}{t_{i+1} - t_i} \quad (2)$$

$$\sigma_i = \frac{P_i\left(H_i^2 + (R_0 + \rho_0)^2\right)}{4s_iH_i}. \quad (3)$$

The values of Backofen's equation constants, $C$ (the strength coefficient) and $m$ (the strain rate sensitivity index) were calculated for the time instants in which a pressure jump was applied ($j$:$P_j \neq P_{j+1}$) as follows:

$$m_j = \frac{\ln(\sigma_{j+1}/\sigma_j)}{\ln(\dot{\varepsilon}_{j+1}/\dot{\varepsilon}_j)}, \quad (4)$$

$$C_j = \sigma_j\dot{\varepsilon}_j^{-m_j}. \quad (5)$$

The material constants calculated for those time instants were linearly interpolated in order to obtain the values of $m_i$ and $C_i$ corresponding to the current value of the effective strain ($\varepsilon_i$). These values are considered to describe the material behaviour during each test at the reference strain rates calculated as the mean value of $\dot{\varepsilon}_i$ and listed in Table 2.

### *Case study produced by SPF*

The biomedical implant to be manufactured by means of the SPF process was designed starting from diagnostic images of the artificial and properly defected skull shown in Fig. 1. The prosthesis was designed according to the defect morphology, thus allowing a perfect matching between the cranial surface close to the defect [24].

SPF experiments were carried out on rectangular Ti blanks (225 mm × 190 mm) cut from the same sheet used for the material characterization. The case study was manufactured using the 2500 kN prototype electro-hydraulic press machine shown in Fig. 2.

**Table 2**
Experimental plan performed at 850 °C by free inflation tests.

| Pressure regime, MPa | Mean equivalent strain rate, $s^{-1}$ |
|---|---|
| 0.25–0.50 | $2.35 \times 10^{-5}$ |
| 0.50–0.75 | $4.62 \times 10^{-5}$ |
| 0.75–1.00 | $1.11 \times 10^{-4}$ |
| 1.00–1.25 | $3.47 \times 10^{-4}$ |
| 1.25–1.50 | $4.65 \times 10^{-4}$ |
| 1.50–1.75 | $1.04 \times 10^{-3}$ |