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Genetic algorithm based inverse analysis for the superplastic characterization of a Ti-6Al-4V biomedical grade

A. Piccininni [a], [*], D. Sorgente [b], G. Palumbo [a]

[a] Politecnico di Bari, Department of Mechanics, Mathematics and Management, Viale Japigia 182, 70126 Bari, Italy
[b] Università degli Studi della Basilicata, School of Engineering, Viale dell'Ateneo Lucano 10, 85100 Potenza, Italy

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ABSTRACT

The inverse analysis approach is recently spreading as a valuable methodology to calibrate constitutive models describing the superplastic behaviour of light alloys. In this work, the superplastic behaviour of a titanium grade for biomedical applications was characterized by means of a Genetic Algorithm based inverse analysis. Free inflation tests at 850 °C were carried out on the Ti-6Al-4V Extra Low Interstitial alloy at two different levels of constant pressure; in addition, a jump pressure test in which the gas pressure was changed during the same test between the same levels was performed. The dome height curve was acquired during each test and subsequently adopted as target data: a simple 2D Finite Element model, in which the material behaviour was implemented using the Backofen power law, was then created to calibrate the material constitutive equation by means of an inverse analysis approach. A set of constants, able to minimize the error between numerical and experimental data, was determined for each investigated load condition. Subsequent numerical simulations, run for validation purposes, demonstrated that the sets determined using as target the data from the free inflation tests under a constant level of pressure were capable of effectively describing the material behaviour only for load conditions close to the ones from which they had been determined. On the contrary, the set of material constants obtained using the same inverse approach but adopting as target data the acquisitions from the jump pressure test, revealed to describe the material behaviour over a wider span of operative conditions.

1. Introduction

Superplastic Forming (SPF) is a sheet forming process capable of exploiting the property of some alloys to achieve superior levels of strain, usually in an isotropic manner, under certain conditions of temperature and strain rate [1]. For this reason, the SPF process is widely adopted for the manufacturing of highly complex niche components for several industrial applications, from biomedical [2] to automotive and aerospace engineering [3]. During the SPF process the blank is clamped between pre-heated tools and it is forced to copy the die cavity geometry by a controlled gas pressure: no drawing occurs during the forming and the control of the final thickness distribution is an aspect of first concern.

The process design is not trivial and the adoption of the numerical approach is an unavoidable step to effectively calculate the pressure profile for the component manufacturing. To create a reliable Finite Element (FE) model, a key point is the proper modelling of the material behaviour: a fast and accurate characterization methodology based on a strain condition resembling the one of the industrial SPF processes is thus necessary.

Several typologies of experimental tests, as for example free inflation, jump pressure, conical die, prismatic die (plane strain condition) and multi-dome tests [4–8] are reported in literature to be more accurate than tensile tests to effectively characterize the superplastic behaviour: experimental data are then used to determine the material constants according to different constitutive equations.

In the last years, the approach based on the inverse analysis for the solution of problems related to the metal forming process has been spreading out [9]: in particular, the choice of the correct experimental data and the definition of robust objective functions play a fundamental role and can dramatically influence the accuracy of the final result. In particular, when the constants of a specific constitutive models are strictly correlated, different sets can ensure a satisfactory fitting thus leading to inaccurate results: as an example, the strength coefficient C and the strain rate sensitivity index m of the Backofen power law ($\sigma = C\dot{\varepsilon}^m$) are strictly interrelated and both affect the dome height evolution during a bulge test [10].

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[*] Corresponding author.
E-mail address: antonio.piccininni@poliba.it (A. Piccininni).

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Table 1
Ti6Al4V-ELI chemical composition.

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

The inverse analysis approach for the material constants evaluation is mainly based on the minimization of the error between experimental and numerical data: starting from this concept, the inverse analysis can be treated as a conventional optimization problem based on the minimization of an error function. In the last twenty years, lots of effort have been spent to evaluate the performance of several algorithms to solve optimization problems: literature reports that the gradient descent method and the evolutionary algorithms are the most widely promising approaches [11]. It is well known that gradient-based and deterministic formulations, despite being characterized by a high convergence rate, can get stuck in local minima (maxima) thus not providing robust and accurate final results. Despite this, material constants modelling the superplastic behaviour of an aluminium alloy have been successfully determined by means of the inverse analysis driven by the Simplex algorithm [12]. On the other hand, Evolutionary Algorithms (EA) are characterized by the highest robustness but a low convergence rate that, however, is not so strongly dependent on the starting values of the input parameters as for the gradient-based formulations. Recent studies demonstrated that an EA-driven inverse analysis for the evaluation of the AA1050 aluminium alloy constants of a thermoelastic-viscoplastic constitutive model resulted more accurate than a descent gradient formulation combined with the Levenberg–Marquardt algorithm [13]. Literature reports several EA formulations and none of them can be universally considered suitable to solve all problems: for this reason, EA formulations are frequently tested on benchmark problems [14,15] comparing specifically-defined performance parameters. The research for novel and more accurate formulations is still open as in the case of the Differential Evolution Algorithm [16], which are considered to be more performing for certain class of problems. Among several EA formulations, genetic algorithms (GAs), based on the evolution theory of Charles Darwin, start from an initial population and create successive generations recombining the DNA of the best individuals by means of the selection, crossover and mutation operators [17]. GAs have been successfully applied for the evaluation of the material parameters belonging to complex constitutive equations [18,19] and, to overcome the limitation of the low convergence rate, have been combined with the Levenberg–Marquardt algorithm and the augmented Gauss–Newton algorithm within an improved hybrid formulation [20].

In the present work, an inverse analysis approach has been applied to characterize the superplastic behaviour of the Ti-6Al-4V Extra Low Interstitial (ELI), commonly adopted in the biomedical field. In particular, following the methodology already presented by the same authors in a previous study [21], the effect of the target data coming from experimental free inflation tests was investigated. The inverse analysis was run as a GA-based optimization procedure coupling a simple 2D FE model with the integration platform modeFRONTIER: dome height evolutions according to time were acquired during free inflation tests both at constant pressure (at 0.5 and 1.0 MPa) and changing the pressure alternatively between 0.5 and 1.0 MPa. Experimental dome height curves were subsequently adopted as a target data: material constants of the Backofen constitutive model were determined for each of the investigated load conditions minimizing the error between numerical and experimental data. Finally, FE simulations were run for validation purposes implementing the constants obtained from each inverse analysis: comparisons were carried out in terms of dome height evolution according to time and thickness distribution.

2. Material & methodology

2.1. *The investigated titanium alloy*

Free inflation tests were performed on circular specimens (D = 80 mm) extracted by a 1 mm thick Ti6Al4V-ELI sheet. The chemical composition of the investigated alloy is reported in Table 1.

The material was purchased in the annealed condition (790 °C for 68 min and then air cooled).

2.2. *Free inflation tests*

A laboratory scale equipment directly mounted on the 200 kN INSTRON 4485 testing machine was adopted for free inflation tests, as shown in Fig. 1a.

The Ti circular specimen was introduced and clamped between the die and the blankholder once reached the test temperature, which was continuously monitored by a K-type thermocouple during both the heating and the bulging phase (see Fig. 1b). The same thermocouple, being connected to a magnetostrictive sensor, was used to acquire the dome height evolution according to time [21].

Free inflation tests were performed at 850 °C, assumed to be the optimal temperature for the investigated Ti alloy [22]. Specimens were inflated under different load conditions: (i) *constant pressure* (indicated in the following as CP tests) and (ii) *jump pressure* tests (indicated as JP

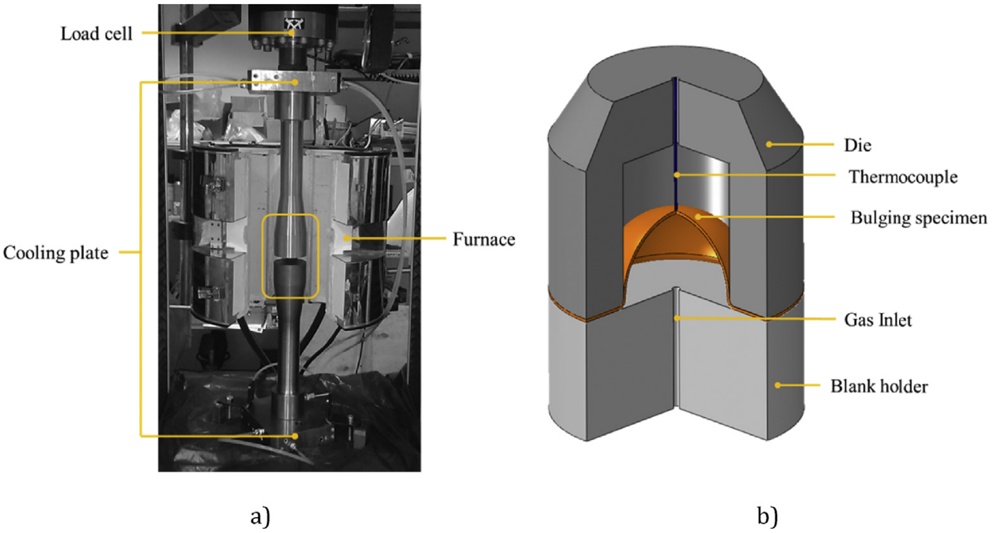

Fig. 1. Laboratory scale equipment for free-inflation tests: a) main components, b) details of the forming chamber.