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ORIGINAL ARTICLE

Modelling the superplastic behaviour of the Ti6Al4V-ELI by means of a numerical/experimental approach

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Abstract In the present work, the superplastic behaviour of a Ti6Al4V-ELI titanium alloy at the temperature of 850 °C is assessed combining experiments and numerical simulations managed by a genetic algorithm-based optimization loop. The experiments consisted of free inflation tests characterized by either a constant gas pressure or several pressure jumps during the same test. Dome height evolutions from tests setting a constant gas pressure were used to evaluate the parameters of the classical strain rate power law material model using an analytical approach from literature. An alternative set of material constants was then evaluated using the inverse analysis based on a genetic algorithm coupled to dome height data from jump pressure tests. Numerical results, in terms of thickness distribution and dome height evolution, obtained from simulations implementing material constants from the inverse analysis fit experimental data in a wider range of strain rates than the ones implementing material constants from the analytical approach.

Keywords Superplasticity · Characterization · *m* value · Ti6Al4V-ELI · Inverse analysis · Finite element

1 Introduction

Material characterization plays a key role in the superplastic forming (SPF) process, since this forming process is strongly based on the numerical simulation. It is almost inconceivable to design a SPF process without a reliable numerical model able to calculate the gas pressure profile to be imposed on the sheet. Only through a preliminary characterization, the optimal process window can be found. In fact, the material behaviour strongly affects the process parameters to be chosen.

Titanium (Ti) alloys are widely and successfully applied in several industrial fields, for example for aerospace, biomedical and architectural applications. When complex-shaped components and/or integrated structures have to be manufactured, SPF is considered the most viable manufacturing process [1]; in addition, it can be combined with conventional stamping processes to obtain higher quality of the final component in terms, for example, of more uniform thickness distribution [2]. A wide and detailed literature on the characterization of Ti alloys in the superplastic field exists and it is well known that the microstructure strongly affects the strain behaviour of the material and, in turn, the strain history strongly affects the microstructure [3]. Virtually, each batch should be characterized ex novo and the chemical composition of the alloy and its mean grain size give not sufficiently exhaustive information about the material. Thus, a fast and accurate characterization methodology based on a strain condition resembling the real forming process is of great industrial interest. Even though the most common procedure to find material constants and optimal processing conditions is based on tensile tests, it has been demonstrated that the corresponding results are not sufficiently accurate for the process simulation [4, 5]. In order to create a biaxial stress state on the sheet, several experimental methods have been developed: free inflation test [6, 7], conical die test [8] and multi-dome test [9], just to cite a few of them. All of these tests are based on analytical assumptions to model the deformation phenomenon. The main drawback of the abovementioned methodologies is that the strain rate cannot be controlled directly as in a tensile test. The gas pressure is imposed on the specimen and

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the strain as well as the strain rate can be indirectly obtained by other macroscopic variables (e.g. the dome height and the thickness). By the analytical assumptions and the measurements, material constants can be calculated. In situ strain measurement during a free inflation test via digital image correlation techniques is another good perspective for the evaluation of material parameters [10]. On the other hand, characterization methods based on the inverse analysis are spreading out in forming applications [11]. The inverse analysis technique was adopted for the identification of material constants but also for the comprehension of material behaviour as a function of the microstructure. Experimental data to be used as reference and the design of the objective function(s) have to be carefully chosen: when correlated material constants are involved, the presence of several sets of fitting constants can lead to not enough accurate solutions. In particular, when the simple power law is used (being the flow stress related only to the strain rate by a power law), both the strength coefficient and the strain rate sensitivity index strongly affect the dome height evolution [12]. This correlation issue can be overcome by the use of objective functions in which there are such variables that are fully (or at least mainly) affected by a single material constant [4]. For characterization purposes, the most important parameter to be evaluated is the strain sensitivity index (m value). Since the extraordinary elongation of superplastic material is related to the diffuse necking which, in turn, is affected by the material strain rate sensitivity, the m value can be considered as a formability index []. Further, this parameter is strictly related to the thickness distribution along the sheet [12]. The international ISO standard for tensile tests on superplastic materials includes also a specimen geometry (R-type specimen) by which the measurement of the m value can be performed through a single standard test [14]. Furthermore, the strain rate jump tensile test, which is also mentioned in the ISO standard, can be carried out to measure the m value using a standard specimen geometry and applying several almost instantaneous strain rate changes (jumps) during a single test.

In recent studies, experimental data by bulge tests were used to find material constants of an aluminium alloy through a minimization procedure based on the simplex method [15] or through a gradient-based algorithm [12]. As in other optimization problems, in an inverse analysis driven by an optimization procedure and aimed at the characterization of a material, local minima (or maxima) could exist. Therefore, the use of algorithms, such as genetic algorithm (GA), that are not affected by the presence of a local minimum (or maximum) is of great advantage. Further, using GA, a population of several candidate solutions evolves instead of studying only one as required by gradient-based optimization techniques [16]. A GA-based multiple objective optimization technique has been developed for determining the material constants in the viscoplastic constitutive equations [17]. Qu et al. used a hybrid optimization technique based on GA using tensile tests data for the material parameter identification of the Ti-6Al-4V alloy [18]. A GA based on tensile test data was also used to determine the material constants of a comprehensive constitutive equation for modelling the behaviour of a Ti alloy taking into account different deformation mechanisms [19]. Li et al. used a GA-driven inverse approach to find the mechanical properties of the weld line (in a butt joint between two different steels). The role of the GA was the minimization of the discrepancies between experimental and numerical stress-strain curve from a tensile test of the joint [20]. With new tremendous potentialities of supercomputing and of parallel computing, the idea that an evolutionary algorithm, such as a GA, could be used also in this optimization problems is not so bizarre. The evolution of tens of *generations* of a population where each *individual* (or *phenotype*) is based on a finite element simulation could be analyzed. Further, with a simple 2D finite element model, thousands of simulations can be run and results can be achieved within a day of automatic computing even on a common workstation.

The aim of the present work is to evaluate the superplastic behaviour of the titanium alloy Ti6Al4V-ELI at the temperature of 850 °C combining experiments and finite element (FE) simulations in a fast inverse GA-based inverse approach. In particular, free inflation tests were carried out setting either a constant gas pressure or several pressure jumps during the same test. Dome height evolutions from tests setting a constant gas pressure were used to evaluate the parameters of the classical strain rate power law material model using an analytical approach from literature. An alternative set of material constants was then evaluated using the inverse analysis based on dome height data from a jump pressure test. Finally, FE simulations implementing material constants from the inverse analysis and from the analytical approach were run and compared to the thickness distribution and to the dome height vs. time curve for validation purposes.

2 Material and methods

2.1 The investigated titanium alloy

Free inflation tests were performed on circular specimens ($D = 80$ mm) extracted from a 1-mm-thick Ti6Al4V-ELI sheet, whose chemical composition is reported in Table 1. The material was purchased in the annealed condition (790 °C for 68 min and then air cooled).

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.

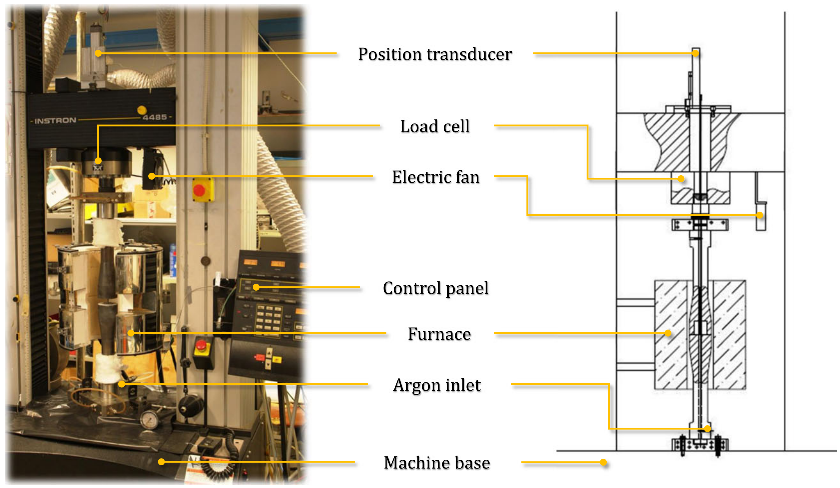


Fig. 1 Main components of equipment for the free inflation test

2.2 Free inflation tests

The laboratory scale equipment shown in Fig. 1 was designed to fit the internal dimensions of an electric three-zone split furnace of an INSTRON universal testing machine.

After the upper and the lower tool reach the test temperature, the blank is introduced between them and serrated. In the upper tool, a cylindrical cavity (diameter 45 mm; entry radius 3 mm) is created into which the Ti alloy specimen can expand freely being inflated by pressurized argon gas. An axial hole passing throughout the whole length of the upper tool allows to measure the temperature in centre of the blank by means of a K-type thermocouple. The same thermocouple is connected to a magnetostrictive transducer to continuously acquire the dome height of the specimen during the test.

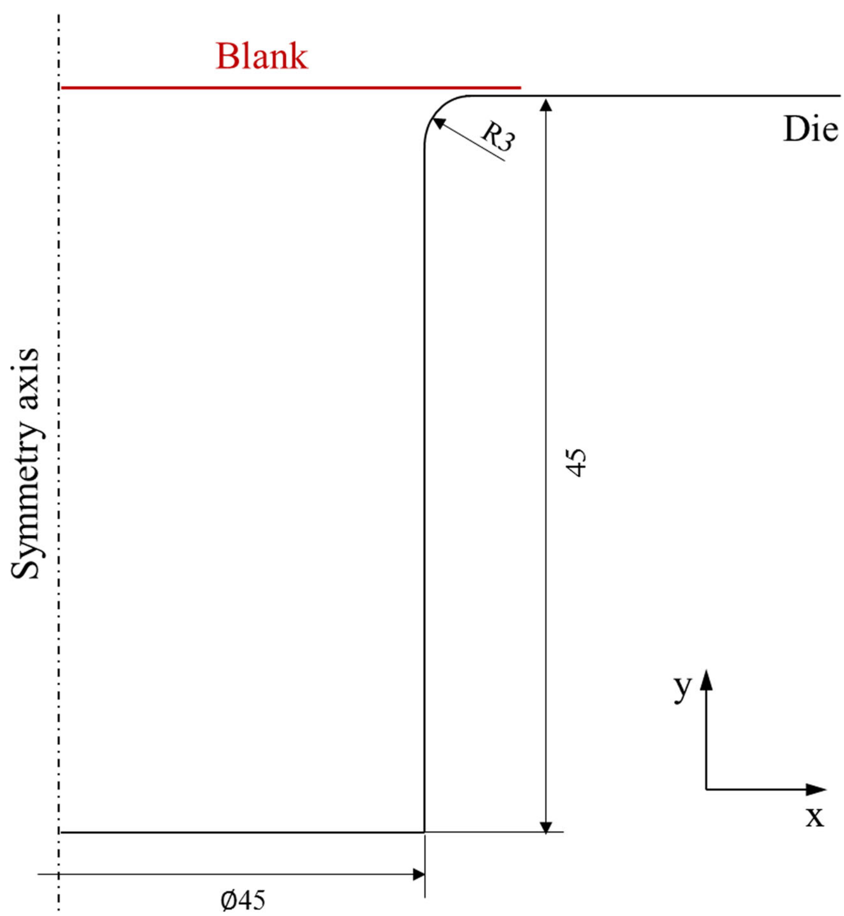


Fig. 2 Numerical model of the free inflation test

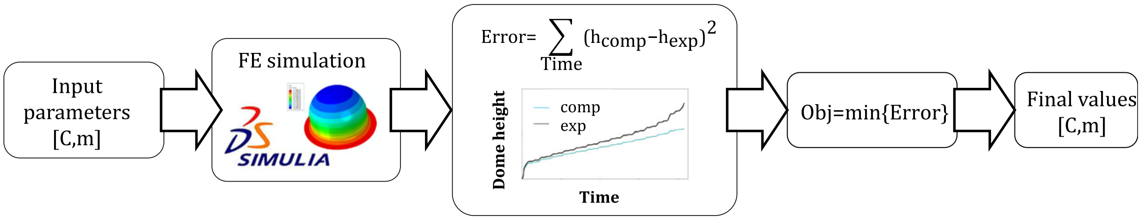


Fig. 3 Schematic overview of the inverse analysis methodology

Two different types of free inflation tests were carried out: (i) setting a constant pressure (CP tests); and (ii) changing the pressure alternatively between two different pressure levels (JP tests) using an electronic pressure regulator managed by a LabView Virtual Instrument. In particular, CP tests were conducted at the following pressure levels: 0.5, 1.0 and 1.5 MPa; while, in JP tests, the pressure was varied between 0.5 and 1.0 MPa. The temperature was set at 850 °C, defined as the optimal value for the investigated ELI Ti alloy, according to the work by Lee et al. [21].

In order to obtain reliable experimental results, each test was replicated twice. Both the dome height evolution (according to time) and the thickness distribution (measured on sectioned inflated specimens) were taken into account in the analyses. Thickness measurements were also replicated (three measurements for each point); the correspondent uncertainty was calculated using a Student's *t* distribution.

2.3 Numerical model

In order to reduce the computational cost, the axisymmetric finite element model (ABAQUS v 6.12) shown in Fig. 2 was used in the present work. Numerical simulations (computational time of about 1 min each) were run on a Xeon 3.47 GHz dual processor with 40 GB RAM installed.

The cylindrical die cavity was modelled as a rigid surface while the blank as a deformable shell (initial thickness 1 mm) meshed with 270 elements (SAX in the ABAQUS element library) with five through-thickness integration points.

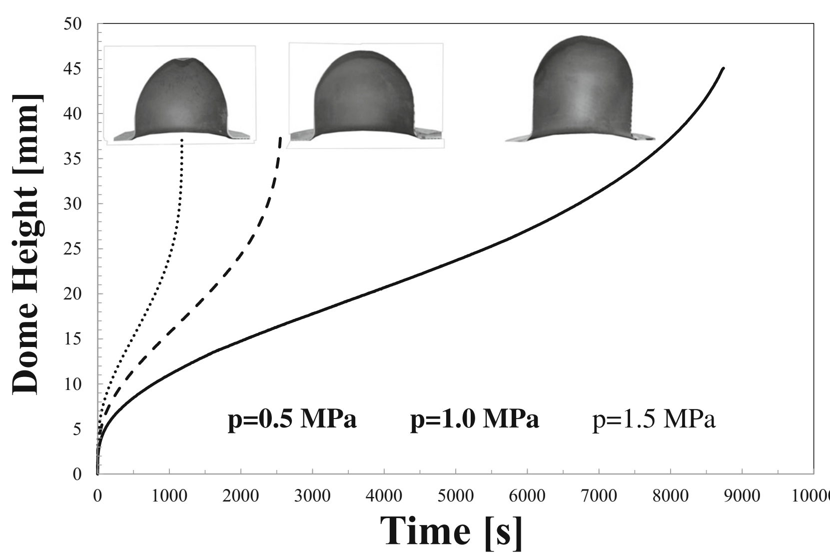
Material constants of the power law model (C, m) were used to implement the material behaviour at the investigated temperature (850 °C). In particular, the constants (A, n) of the Bailey-Norton power law (available in ABAQUS), where the creep strain rate is $\varepsilon = A\sigma^n t^p$, were determined, while the time exponent p was set equal to zero. In this formulation, $n = 1/m$ and $A = (1/C)^{1/m}$.

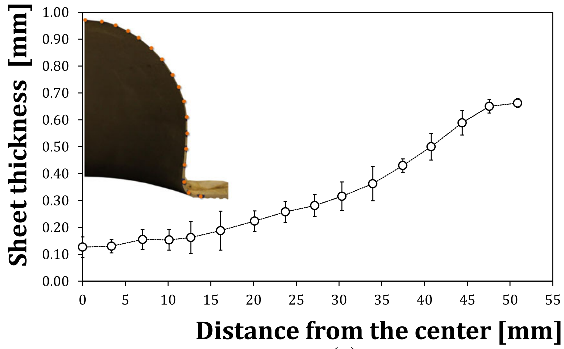
2.4 Inverse analysis methodology

Since the elasto-viscoplastic behaviour was modelled adopting the power law $\sigma = C\varepsilon^m$ as constitutive equation, material constants were evaluated using the inverse analysis approach summarized in Fig. 3.

In order to determine optimal values for the parameters set as input variables of the system under investigation, an objective function based on parameters set as output variables has to be properly defined. In this work, the acquired dome height evolution was chosen as the output variable and the objective function to be minimized and reported in Eq. (1) was adopted for evaluating optimal values of the input variables (C, m):

Fig. 4 Dome height vs. time curves in CP free inflation tests





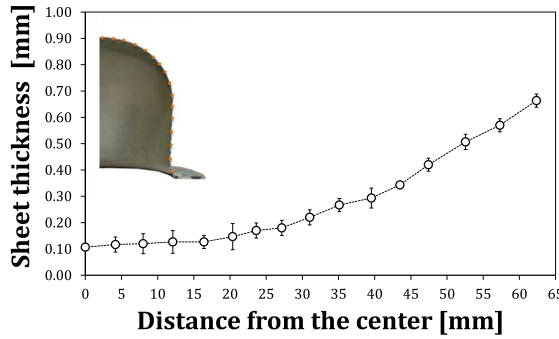


Fig. 5 Thickness profiles on specimens tested using a constant pressure level of 1.0 (**a**) and 0.5 MPa (**b**)

$$\text{Error} = \sum_{\text{time}} \left(h_{i,\text{comp}} - h_{i,\text{exp}}\right)^2 \quad (1)$$

where $h_{i,\text{comp}}$ is the numerically computed dome height value at the ith instant of time and $h_{i,\text{exp}}$ is the correspondent experimental value. In particular, the dome height evolution obtained using the JP test was used for the inverse analysis and, according to Eq. (1), the goal of the optimization procedure was to determine the values of the material constants able to optimally fit the experimental curve (i.e. to minimize the error between the numerical and the experimental dome height evolution). Although more than one curve from different replications was available, the dome height evolution from a single test was considered as the reference for the inverse analysis, since the averaging of curves between different tests would lead to a change in character on the slope change due to the pressure jump. In fact, the slope change is strictly related to the strain rate sensitivity index, such a curve feature has thus to be preserved. The uncertainty of the calculated material constants can be estimated a posteriori knowing the effect of a change in the curve on the results of the characterization. Nevertheless, the resulting uncertainty is assumed to be not greater than the one calculated using analytical models or fitting tensile tests data in a conventional characterization procedure.

In order to find optimal C and m values, the FE model described in Section 2.4 was embedded in the optimization loop: the optimization procedure started from an initial population of 50 designs (each design represents a couple of values for the input variables C and m) which were uniformly distributed within the design space adopting the Sobol algorithm [22]; then, the simulation was automatically run and results collected in terms of dome height evolution in order to calculate the error function.

3 Results

3.1 Experimental results

In this section, experimental results from free inflation tests are presented in terms of dome height evolutions and thickness profiles of superplastically formed specimens after mechanical cutting.

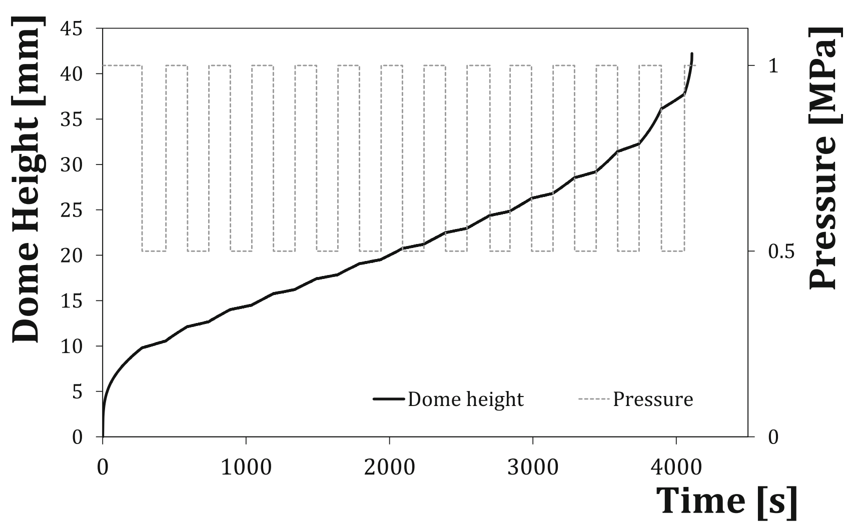


Fig. 6 Dome height vs. time curves in JP free inflation tests

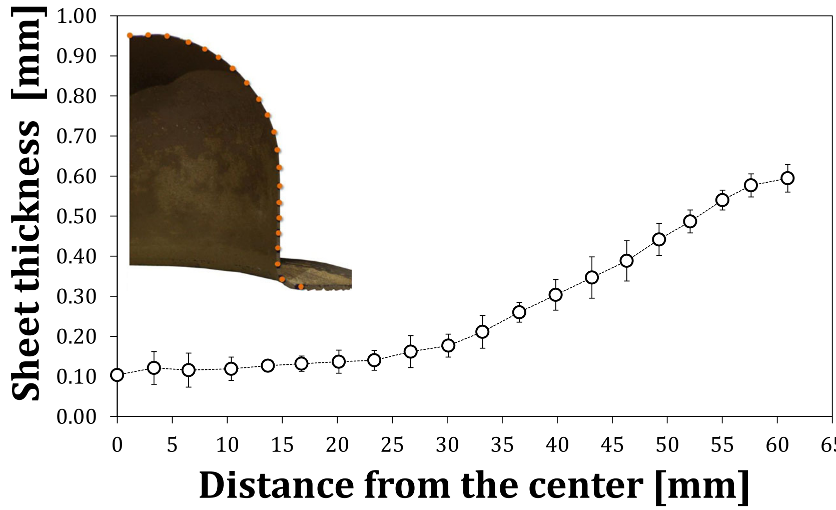


Fig. 7 Thickness evolutions on specimens tested using the JP methodology

3.1.1 Constant pressure free inflation tests

In Fig. 4, results of CP free inflation tests have been reported together with the pictures of the cross-sectioned specimens.

It can be clearly seen that the rate of deformation is not linearly related to the pressure value, and that the maximum height the material can reach at failure depends on the pressure and, in turn, on the strain rate. In order to calculate the value of the strain at failure, the thickness distribution along the section was measured after cutting the formed specimens. Due to the balanced biaxial stress condition, the thickness at the dome apex could be used for calculating the true equivalent strain in such a location (the true equivalent strain was calculated as the natural logarithm of the ratio between the initial and the final thickness).

Figure 5 shows the thickness profiles as a function of the distance from the centre of the specimen for (a) the one obtained setting a constant pressure level of 1 MPa; (b) the one obtained setting a constant pressure level of 0.5 MPa.

In the latter load condition (Fig. 5b), the specimen touched the bottom surface of the die cavity without rupture (the test was stopped when the height of the specimen reached the depth of the die).

In both cases, the largest thinning was observed in the dome apex area: the measured thickness is approximately equal to 0.1 mm and, in the case of the specimen tested setting the pressure to 0.5 MPa, a larger area characterized by high thinning is present. The uncertainty on thickness experimental measurements is in the range 0.017–0.072 mm.

3.1.2 Jump pressure free inflation tests

Figure 6 shows the profiles of both the dome height (continuous line) and the gas pressure (dashed line) obtained in the JP free inflation test.

Since in the CP tests at the lowest gas pressure levels (0.5 and 1.0 MPa) the highest dome height values were reached, such levels were assumed to define the optimal range of pressure for the investigated alloy. As a consequence, the gas pressure in the JP free inflation test was switched every 300 s between the values of 0.5 and 1.0 MPa.

It can be noted that the dome height evolution is characterized by a discontinuous trend due to the variation of the forming pressure between the explored levels.

In Fig. 7, the thickness profile as a function of the distance from the centre is reported for the specimen subjected to the JP test. As in previous cases, the minimum thickness is located at the dome apex and both its value (approximately 0.1 mm) and its uncertainty (in the range 0.014–0.051 mm) are very similar.

3.2 Material constant evaluation

3.2.1 Enikeev and Kruglov approach

Using data from CP tests, the strain rate sensitivity index was calculated adopting the analytical model proposed by Enikeev

Table 2 Material constants from the analytical model proposed by Enikeev and Kruglov [23]

Material constants	Analytical model
C [MPa s^m]	6421
m [−]	0.746

Table 3 Variation ranges of the input parameters adopted by the genetic algorithm

Input variables	Lower value	Upper value
C [MPa s^m]	3000	9000
m [−]	0.3	0.9

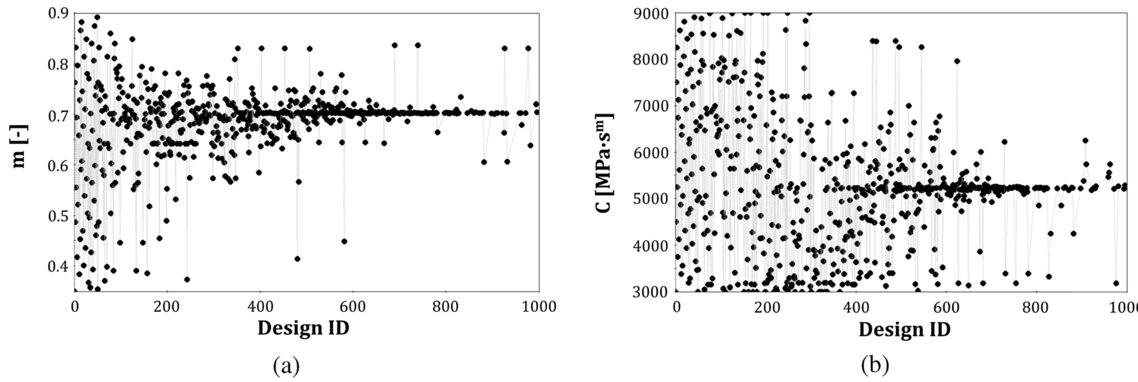


Fig. 8 History charts from the genetic algorithm in the optimization procedure. **a** *C* value **b** *m* value

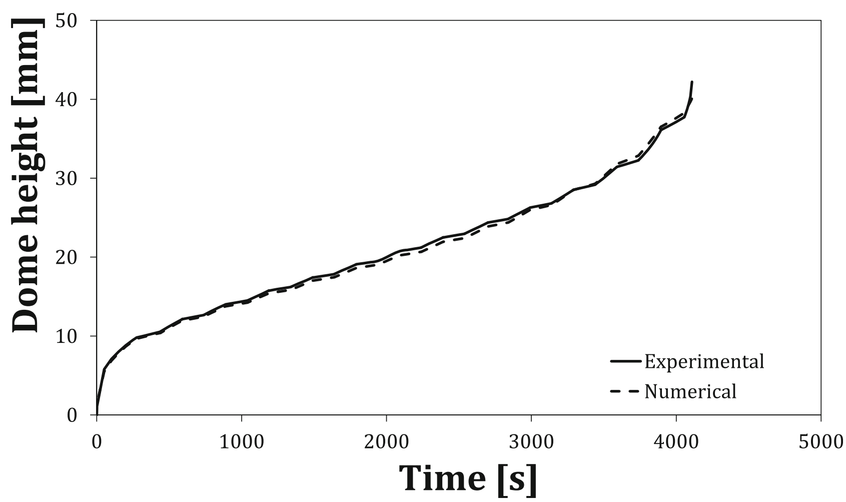


Fig. 9 Results of inverse analysis: experimental data vs. best numerical design

and Kruglov [23]. Such a methodology allows to evaluate the material constants (*C* and *m*) of the power law model using data from two tests with two different (constant) pressure levels. Table 2 details the obtained material constants.

3.2.2 Inverse analysis approach

Starting from results coming from the first population, the genetic algorithm adopted in the inverse analysis freely evolved through 20 successive generations adopting the mutation and the crossover operators [24], thus globally managing 1000 numerical runs.

Variation ranges of the input parameters adopted in the optimization procedure are detailed in Table 3. Such ranges were defined using as reference the results from the analytical model that was previously applied; in particular, values of material constants coming from such an analytical approach (see Section 3.2.1) were approximately positioned in the middle of the adopted ranges.

Table 4 Material constants obtained from the inverse analysis

Material constant	Inverse analysis
C [MPa s^m]	5229
m [−]	0.703

Results obtained by the inverse analysis are presented in Fig. 8a, b in terms of history charts describing the evolutions of the two above defined input variables over the whole optimization procedure (each black dot refers to a single numerical simulation).

It is worthy of notice that, since no constraint was applied, the genetic algorithm freely evolved towards the values of both the input variables which can be defined as “optimal”, thus making the obtained results robust. The proposed procedure resulted to be quite fast, since it took less than 1 day (20 h and 26 min) to run and analyze all the 1000 designs.

The effectiveness of the proposed methodology is further confirmed by Fig. 9 in which the experimental dome height evolution (continuous black line) is compared to the numerical one (dashed black line) obtained using the best design, i.e. the one characterized by the lowest value of the error function (see Eq. (1)).

Table 5 Thickness values in the dome apex at failure and calculated strain and strain rate

Pressure [MPa]	Thickness [mm]	Dome height at failure [mm]	Equiv. strain [–]	Equiv. mean strain rate [s^{-1}]
0.5	0.11 ± 0.018[a]	Greater than 45	2.192[a]	2.50×10^{-4}
1.0	0.12 ± 0.013	39.6 ± 0.74	2.120	8.30×10^{-4}
1.5	0.10 ± 0.011	36.6 ± 0.50	2.354	1.18×10^{-3}

[a] The specimen touched the bottom of the die cavity (45 mm deep) without failure

Table 6 Material constants implemented in FE simulations

Material constant	Inverse analysis	Analytical model
C [MPa s^m]	5229	6421
m [–]	0.703	0.746

Table 4 contains the values of the material constants (C and m) evaluated using such a methodology.

4 Discussion

4.1 Superplastic behaviour of the investigated alloy

Values in Table 5 (average of experimental data) confirm that the investigated Ti alloy exhibits a superplastic behaviour at the temperature of 850 °C.

In fact, an equivalent strain at failure up to 2.3 was observed in this material for the applied pressure levels. The maximum strain value was obtained for (mean) strain rates between ~10^{-4} s^{-1} and ~10^{-3} s^{-1}, which are quite close to the values indicated by Lee et al. [21] as optimal for the same ELI grade of the Ti alloy at the same temperature level.

If the gas pressure is decreased a correspondent strain rate reduction is obtained. At the lowest pressure value, the material filled the die touching the bottom of the die cavity without any fracture occurrence. In such a situation, the equivalent strain (as reported in Table 5) is not the maximum strain at failure that the material can experience. It can be thus stated that, setting the pressure to 0.5 MPa, the resulting strain rate determines the optimal investigated forming condition for this alloy, since the achieved final height (greater than 45 mm) is significantly larger than the values achieved in other conditions.

4.2 Validation of the approach

Results in terms of different material models were implemented in further FE simulations setting two different load conditions, both characterized by constant pressure values 0.5 and 1.0 MPa, respectively. In particular, material constants adopted for simulations are reported in Table 6.

Numerical results were collected in terms of thickness distributions along the radial direction considering in the final deformative conditions (specimens at the end of the test). Corresponding experimental data were included in the graphs and used for evaluating the effectiveness of FE models implementing different sets of material constants.

In Fig. 10, numerical and experimental thickness profiles at the end of the tests carried out setting the pressure to 0.5 and 1.0 MPa have been compared.

It is interesting to note that both FE models (the one implementing material constants obtained from the inverse analysis and the one implementing material constants from the analytical approach) fit very well the experimental trends (circular markers). Much larger differences between numerical results from simulations implementing the two different

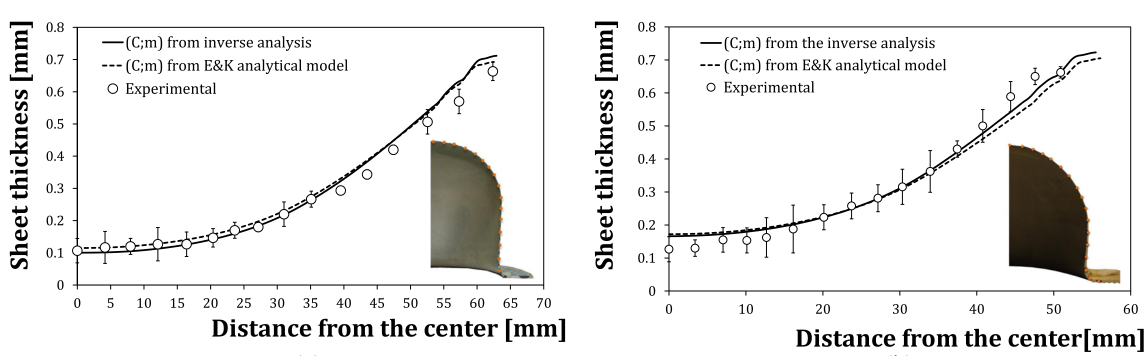


Fig. 10 Numerical vs. experimental thickness distribution in CP tests: **a** p= 0.5 MPa. **b** p= 1.0 MPa

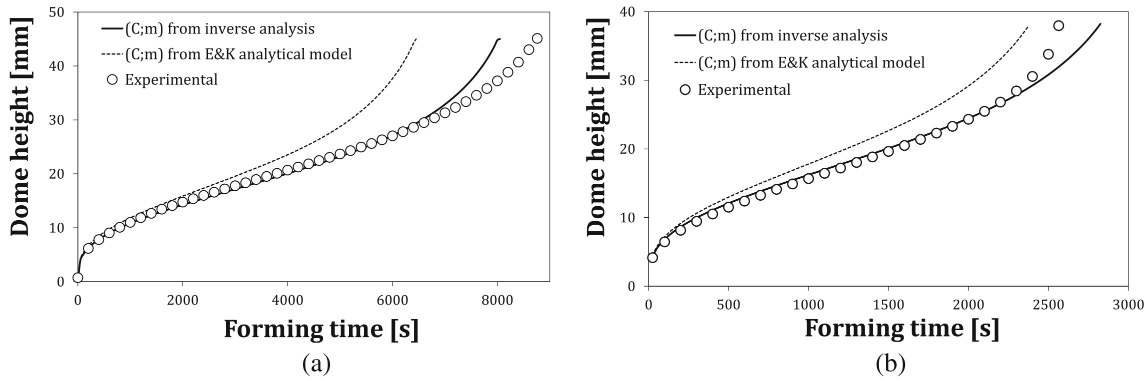


Fig. 11 Numerical vs. dome height evolution in CP tests: **a** $p = 0.5$ MPa. **b** $p = 1.0$ MPa

sets of material constants can be found when considering the comparison with experimental dome height evolutions. In fact, as shown in Fig. 11, a good fitting between experimental data and results obtained from the numerical simulations implementing the material constants determined by the inverse analysis was obtained when setting both the (constants) pressure levels.

On the contrary, material constants determined by the analytical model could not properly predict the evolution of the blank deformation.

In Table 7, the values of the error calculated as difference over the whole duration of the test between the numerical and experimental dome height evolutions have been listed for the sake of clarity.

While for the thickness prediction both the models gave a good agreement, the prediction of the dome height evolution is much more accurate if the material constants achieved by the inverse analysis are adopted.

5 Conclusions

With the aim of assessing the superplastic behaviour of the Ti-6Al-4V ELI alloy at 850 °C, material constants of a simple constitutive equation based on power law have been evaluated through two different approaches. The first one is a well-known methodology based on analytical assumptions. The second one is an inverse approach based on the minimization of the discrepancy between numerical and experimental results. Comparing results from these two different approaches, the following conclusions can be drawn:

Table 7 Evaluation of the average percentage error

	$p = 0.5$ MPa	$p = 1.0$ MPa
Inverse analysis	3.47 %	3.77 %
Analytical model	16.02 %	16.70 %

- The adopted experimental methodology based on gas pressure jumps resulted to be an optimal reference test for the inverse analysis.
- Both sets of material constants (the one from the analytical approach and the one from the inverse analysis methodology) led to a good prediction of the experimental thickness distribution (maximum errors under 10 %).
- Only the set obtained using the inverse analysis approach allowed to properly fit experimental dome height evolutions acquired during tests at constant pressure levels; such a good fitting (mean error lower than 4 %) was obtained both at the pressure of 0.5 MPa and at the pressure of 1.0 MPa, thus revealing the robustness of the proposed approach and the adequacy of considering as the reference for the inverse analysis a single curve.

Results from this inverse approach demonstrated excellent suitability of the evaluated rheological model and of the characterization technique for being used in numerical simulations of superplastic forming processes.

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