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Parameters identification in strain-rate and thermal sensitive visco-plastic material model for an alumina dispersion strengthened copper

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ABSTRACT

The main objective of this paper is getting strain-hardening, thermal and strain-rate parameters for a material model in order to correctly reproduce the deformation process that occurs in high strain-rate scenario, in which the material reaches also high levels of plastic deformation and temperature. In particular, in this work the numerical inverse method is applied to extract material strength parameters from experimental data obtained via mechanical tests at different strain-rates (from quasi-static loading to high strain-rate) and temperatures (between 20 °C and 1000 °C) for an alumina dispersion strengthened copper material, which commercial name is GLIDCOP®. Thanks to its properties GLIDCOP® finds several applications in particle accelerator technologies, where problems of thermal management, combined with structural requirements, play a key role. Currently, it is used for the construction of structural and functional parts of the particle beam collimation system. Since the extreme condition in which the material could operate, it is fundamental to characterize it in a wide range both in strain-rate and temperature.

The numerical inverse method used in this work is particularly useful to reproduce experimental results when the stress–strain fields in the specimen cannot be correctly described via analytical models. Furthermore this procedure is useful to take into account thermal phenomena generally affecting high strain-rate tests in which the heat conversion of plastic work produces an adiabatic overheating. So, the applicability of this method is particularly indicated in special fields, such as aerospace engineering, ballistic, crashworthiness studies or particle accelerator technologies.

The attention is focused on evaluating the most suitable strategy of material model parameters optimization to obtain the best fit between experimental data and numerical results. In this regards, it is important to determine which material model coefficients can be considered as optimization variables and for each of them the most suitable range of variation.

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1. Introduction

The description of the relationship between stress and strain for a material implies the identification of work hardening, strain-rate sensitivity and thermal softening parameters in order to correctly reproduce the experimental material response with a specific material model.

If the material model is completely physically-based the model parameters are correlated to the physics and chemical material properties. Otherwise, if the material model is empirical (phenomenological), it is necessary to obtain the model coefficients and, usually, the approach is fitting the experimental data analytically. With this standard approach, the quality of the results could be affected by geometrical effects, that lead to non uniform stress–strain field within the specimen, and thermo-mechanical coupling in case of high strain-rates, when the thermal softening effects become more relevant. On the other hand, a numerical inverse method is useful to extract material strength parameters from experimental results in all the cases in which the stress and strain fields are not correctly described or predictable with an analytical model. Usually, this happens in specimens with no regular shape, in specimens in which some instability phenomena occur (e.g. the necking phenomena in tensile tests) or in dynamic tests, in which the strain-rate field is not uniform due to the stress wave propagation. Besides, the inverse method is also useful in case of high strain-rate tests, in which the adiabatic heating due to

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plastic work conversion into heat leads to thermal softening phenomena.

The use of a numerical inverse method for the material model parameters identification is now widespread thanks to the larger computing power available at lower cost. In any case, the difficulty is often the understanding of which are the best strategies to choose to take advantage of the capabilities of the optimization methods applied to problem like system parameters identification.

In recent years, different authors applied a combined numerical and experimental technique with the aim to extract the material model parameters via an inverse method. One of the most important works on this topic is [1]. A specific treatment was developed according to the choice of the material model [2,3], the type of the experimental tests [4,5], the FEM code for the numerical solution and the algorithm on which the optimization was based on [6,7]. A lot of these works are related with the solution of problems in which the dynamic component could be relevant. For these reasons, the material behavior description was based on the definition of a visco-plastic material model and the experimental tests covered a wide range of strain-rates, from quasi-static up to high strain-rates. Since the loading conditions to simulate, often an explicit FEM code was used, like LS-DYNA, RADIOSS, AUTODYN and ABAQUS. Finally, the choice of the optimization algorithms was linked to the algorithms that are implemented in the commercial optimization codes, like LS-OPT and HYPERSTUDY.

The main objective of this work is getting strain-hardening, thermal and strain-rate parameters for a material model in order to correctly reproduce the deformation process in a wide range of temperature and strain-rate via a numerical inverse method of which the main steps of the procedure are as follows.

- Performing the experimental tests at different speeds and temperatures.
- Optimizing the material parameters via numerical FEM simulation of the experimental tests using the commercial code LS-OPT [8] for the optimization phase and LS-DYNA [9] for the numerical simulations.

It is important to remark that a material characterization must count on a specified analytical model from which the number of strength parameters and the types of experimental tests to be performed depend. For this reason, it is very important that experimental tests and numerical modeling go hand in hand in order to avoid both an inadequate and an overflowing number of data. So, first of all it is necessary to choose the material model on which it is consequently possible to plan the experimental tests. Then, the numerical model of each experimental test is realized. The next aspect is the evaluation of the most suitable strategy of the parameters optimization estimating the influence of each model parameter on both the stress–strain relationship and the optimization error. Finally, once the best optimization strategy has been identified, it is possible to apply the numerical inverse method to extract the numerical model parameters for the investigated material.

2. Material model

In the past decades a lot of material models for the description of the elasto-visco-plastic behavior are proposed. The classification model makes a distinction between empirical, semi-empirical and physically-based models. The empirical models have no physical basis, but are obtained by interpolation of the experimental data. On the other hand the physically-based models are obtained starting from transformations in the material occurring during a deformation process.

Models such those proposed by Johnson–Cook (J–C) [10,11] and Cowper–Symonds (C–S) [12] are purely empirical models and they are the most widely used. An example of semi-empirical model is the Steinberg–Cochran–Guinan–Lund (S–C–G–L) model [13,14], which was first developed for the description of high strain-rates behavior [13], and after extended to low strain-rates [14]. Another semi-empirical model is the Zerilli–Armstrong (Z–A) model [15] that is obtained on the basis of the dislocation mechanics theory and presents different formulations for BCC and FCC materials. A more complex dislocation-based model is the Mechanical Threshold Stress (MTS) model [16].

The chosen material model for the numerical simulation is the J-C model because, since it is very simple, it is able to predict the mechanical behavior of the materials under different loading conditions. Besides, as mentioned before, it is one of the most used material models, so it is implemented in many FEM codes.

Several authors used the J–C model, or its modified formulations, in order to investigate and describe problems such as ballistic impacts or, more in general, problems in which the strain-rates component was relevant. Different methods for the material model calibration starting from experimental data were also suggested. A lot of different types of materials have been described using the J–C model, such as steels [17,18], aluminum alloys [19,20], titanium alloys [21–23], OFHC copper [24,25], tungsten alloy [26] and super alloys [27], with mainly application in automotive, aerospace, nuclear and military fields. In some cases, the experimental data were fitted on the basis of the analytical formulation of the material model, while other works performed the calibration of FEM models starting from experimental results.

Recently, a multi-objective procedure for the material model identification has been proposed in [26]. In the present paper, a similar approach is presented, but differently from [26], the method is based on the use of FEM models, in order to take into account also the development inside the specimen of non-homogeneous distribution in mechanical quantities (stress, strain, temperature and strain-rate).

2.1. Johnson–Cook model

The standard J–C model [10] expresses the flow stress as

$$\sigma_y = \left(A + B\varepsilon_{\mathrm{pl}}^n\right)\left(1 + C\ln\frac{\dot{\varepsilon}_{\mathrm{pl}}}{\dot{\varepsilon}_0}\right)\left(1 - \left(\frac{T - T_{\mathrm{r}}}{T_{\mathrm{m}} - T_{\mathrm{r}}}\right)^m\right) \tag{1}$$

in which A is the elastic limit strength and fixes the stress value at which the plastic behavior starts, B and n are the work hardening parameters and influence the slope of the flow stress in the plastic domain. The parameter n usually assumes values between 0 (for perfectly plastic model) and 1 (for a bilinear model). C is the strain-rate sensitivity coefficient and m describes the thermal softening. In more detail, m determines the concavity of the temperature function: if $m < 1$ the function is convex, if $m > 1$ it is concave and if $m = 1$ the temperature influence is linear. The thermal effects are also described in function of T_{r} that is the reference temperature at which there are not any thermal effects and T_{m} that is the melting temperature at which the material mechanical strength goes to zero. In this condition the material loses its shear strength and starts to behave like a fluid.

In the LS-DYNA formulation [9], $\dot{\varepsilon}_0$ represents the quasi-static strain-rate threshold that represents the highest strain-rate for which the strain-rate effects on the flow stress are negligible.

The J–C model is a multiplicative model, in which the effects of plastic strain, strain-rate and temperature are assumed to act independently. It is clear from the Eq. (1) that a strain-rate or temperature variation implies only a scaling and not a modification

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