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Peroni, M (Politecnico di Torino) *et al*

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Thermo-mechanical model identification of a strengthened copper with an inverse method

M. Peroni¹, L. Peroni¹ and A. Dallochio²

¹ *Department of Mechanics, Politecnico di Torino – C.so Duca degli Abruzzi 24, 10129 Torino, Italy*

² *Engineering Department – Mechanical and Materials Engineering Group, CERN (European Organization for Nuclear Research), 1211 Geneva 23, Switzerland*

Abstract. This paper describes a numerical inverse method to extract material strength parameters from the experimental data obtained via mechanical tests at different strain-rates. It will be shown that this procedure is particularly useful to analyse experimental results when the stress-strain fields in the specimen cannot be correctly described via analytical models. This commonly happens in specimens with no regular shape, in specimens with a regular shape when some instability phenomena occur (for example the necking phenomena in tensile tests that create a strongly heterogeneous stress-strain fields) or in dynamic tests (where the strain-rate field is not constant due to wave propagation phenomena). Furthermore the developed procedure is useful to take into account thermal phenomena generally affecting high strain-rate tests due to the adiabatic overheating related to the conversion of plastic work.

1. INTRODUCTION

Aim of this work is to present a combined experimental and numerical technique, based on an inverse approach, to identify work-hardening, strain-rate sensitivity and thermal softening parameters of different material models applied to a dispersion strengthened copper. Stress-strain relationships are usually obtained by fitting experimental data with analytical models, however the quality of results obtained with this standard approach, could be affected by geometrical effects (triaxiality of the stress and strain fields) and by the thermal coupling in case of high strain-rate. An inverse method is useful to optimize material strength parameters extracted from experimental results when the stress-strain fields in the specimen are not correctly described by the analytical models. That commonly happens in specimens with no regular shape, in specimens with regular shape when some instability phenomena occur (for example the necking phenomena in tensile tests that create a strongly heterogeneous stress-strain fields) or in dynamic tests (where the strain-rate field is not constant due to wave propagation phenomena). The inverse method described in this paper relies on three main steps:

- experimental compressive and tensile tests performed at different speeds and different temperatures, from quasi-static loading to high strain-rate;
- experimental results fitted with analytical models in order to obtain reference material strength parameters;
- optimization of material strength parameters via numerical FEM simulations of the experimental tests.

It is important to remark that an effective material characterization must count on a specified analytical model from which depend the number of strength parameters and types of experimental tests to be performed. Next paragraph describes the analytical models used for this study.

2. MATERIAL MODELS

Elasto-plastic strain-rate sensitive models such those proposed by Johnson and Cook (J-C) [1] and Cowper-Symonds (C-S) [2], are the most used to describe work-hardening, thermal softening and strain-rate sensitivity behaviour of ductile materials. Commercial FEM code LS-DYNA® [3], used for numerical simulations described in next paragraphs, allows to define a material model including strain-rate effect from C-S or J-C and thermal softening from J-C as shown in (1):

$$\sigma = \begin{cases} A + B\varepsilon_p^n \\ K\varepsilon^n \\ \text{piecewise} \end{cases} \cdot \begin{cases} 1 + C \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \\ 1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{1/q} \end{cases} \cdot (1 - (T^*)^m) \quad (1)$$

In (1) A is the elastic limit, B , n and K are the work hardening parameters, C , $\dot{\varepsilon}_0$, D and q are the strain-rate sensitivity parameters, T^* and m are the thermal parameters. Thermal softening phenomena are essentially due to heat conversion of plastic work occurring at high strain-rate where strain is localized (as it will be confirmed via numerical simulations); for about $\dot{\varepsilon} \geq 10^2 \text{ s}^{-1}$, thermal diffusion can be neglected and thermal softening can be evaluated under adiabatic assumption. Given this last hypothesis and the further assumption of uniform stress, strain and temperature field, the material temperature can be analytically computed as a function of plastic work as shown in expression (2).

$$T = T_r + \frac{\beta}{\rho \cdot C_p} \cdot \int_0^{\varepsilon_p} \sigma(\varepsilon, \dot{\varepsilon}, T) \cdot d\varepsilon \quad (2)$$

In expression (2) ρ is the material density, C_p is the specific heat at constant pressure and β is the Taylor-Quinney coefficient [4, 5] that represents the portion of plastic work that is converted into heat (for metals about 0.9).

Figure 1. Scheme of the Hopkinson tensile bar set up and the specimen used in tensile test.

3. EXPERIMENTAL TESTS

Object of this study is a dispersion strengthened copper, known by the trade name GLIDCOP, that finds several applications in particle accelerator technology, where problems of thermal management combined with structural requirements play a key role [6]. In fact, Glidcop has material properties similar to OFE copper, such as thermal and electrical conductivity. Unlike OFE Cu, however, Glidcop has yield and ultimate strengths equivalent to those of mild-carbon steel, making it a good structural material. Experimental compressive and tensile tests were

Figure 2. (a) Engineering stress-strain curves from quasi-static tensile tests at different temperatures; (b) true stress-true plastic strain curves from quasi-static compressive tests at different temperatures; identification of work hardening and thermal softening parameters by fitting experimental data with J-C analytical model.

performed at different speeds (10^{-3} , 10^{-1} , 10 , 10^3 s $^{-1}$) and different temperatures (233, 263, 293, 323, 353 K). Quasi-static loading condition was obtained via general purpose hydraulic testing machine while medium strain-rates tests were performed with pneumatic equipments [7]. High strain-rates compressive tests were carried out with a Split Hopkinson Pressure Bar [8] while tensile tests were performed via a customized direct set up (Figure 1) developed from the solution proposed in [9].

Figure 1 shows a scheme of the developed equipment with a detail of the specimen clamping system and the Lagrangian wave propagation diagram during a test. In this SHPB tensile setup, the striker bar and the input bar are hollow cylinders while the output bar (that is a classical cylindrical bar) is coaxial with the input bar. The test starts generating a compression pulse in the input bar because of the impact of the tubular striker bar. When the compression pulse reaches the opposite extremity of the input bar it applies a tensile stress on a plate that is fixed on one threaded specimen end. In this way the compression pulse applies a tensile stress also to the specimen carrying out the tensile test.

Results of compression and tensile tests performed at different strain-rates and temperatures are shown in Figure 2 and Figure 3. Experimental data were fitted with J-C and C-S analytical models in order to obtain work hardening, thermal softening and strain-rate sensitivity parameters. These reference values (see Table 1) can be optimized via numerical procedure as described in the next paragraph.

4. NUMERICAL INVERSE METHOD

Reference parameters of the material, obtained by fitting experimental curves with analytical J-C and C-S models, have been implemented into a FEM code in order to numerically simulate all the experimental tests previously performed. FEM models have been developed with the commercial code LS-DYNA® [3] which includes implicit and explicit solver with thermo-mechanical and highly non-linear capabilities. In order to reduce CPU time and to staunchly reproduce experimental tests, FEM models only include the specimen to which is applied a load history directly registered from testing equipments. In particular, for high strain-rate tests, the load applied to the specimen by input and output bars of the SHPB, is reconstructed and implemented into the FEM model with the elaboration techniques proposed in [8]. Figure 4.a shows an example of wave velocity profiles applied to compression rigid plates of the FEM models concerning a SHPB test at a strain-rate of 2000 s $^{-1}$.

Figure 3. Dynamic tensile (a) and compression (c) tests at different strain-rates. Identification of material strain-rate sensitivity parameters obtained by fitting experimental data with J-C and C-S analytical models (b,d).

Figure 4. (a) Example of velocity profiles imposed to the compression plates of a FEM model of SHPB test; (b) stress distribution in static compression test; (c) strain-rate distribution in dynamic tensile test.

Numerical simulations provided results having significant discrepancy with respect to the experimental data as shown in Figure 6. In fact, reference parameters of the material have been obtained from experimental data with a standard fit relying on the following assumptions:

- *uniaxial stress and strain inside the specimen.* Actually, three-axial stress and strain fields inside the specimen are caused by the friction (between specimen and testing equipment) during compressive tests (Figure 4.b) and by the necking of the specimen during tensile tests;

Figure 5. Example of thermal field of specimen tested at a strain-rate of 10^{-3} s^{-1} , 10^{-1} s^{-1} and 10^3 s^{-1} in thermo-mechanical coupled simulations.

Figure 6. Optimization of parameters: (a) work-hardening in static compressive test (J-C model); (b): Thermal parameters on compression tests at different temperature (J-C model); (c,d): strain-rate sensitivity parameters on compression and tensile tests (J-C model).

- *constant strain-rate inside the specimen.* Actually the strain rate is not constant and uniform during dynamic tests (Figure 4.c), thus influencing strain-rate sensitivity parameters;
- *uniform temperature inside the specimen.* Actually the temperature has a certain distribution proportional to the distribution of plastic strain inside the specimen, and the effect is even higher for dynamic tests (see Figure 5). This should be considered to identify material strength parameters.

Aim of the inverse method is to optimize material parameters in order to correctly reproduce experimental tests with FEM calculations. Core of this procedure consists of iteratively solving numerical simulations having the experimental curves as objective functions. Optimization of the parameters has been performed with dedicated algorithm included in the software HyperStudy®.

It is important to remark that in J-C and C-S models, work-hardening, thermal sensitivity and strain-rate effects are linearly independent. This allows to separately optimize each set of parameters. Numerical simulations include all experimental tests performed at different speeds and temperatures. The optimization algorithm works with a multiple objective function, this requires to run simultaneously all the simulations relative to a specific set of parameters that must be optimized. Tensile and compressive behaviour of the material was separately evaluated. Results of the numerical optimization are shown in Figure 6 where the advantage of using optimized parameters is evident. The curves labelled standard fit (obtained from numerical model introducing analytical strength parameter) obviously fit experimental less accurately (because of friction and triaxial stress filed).

Table 1 contains reference parameters (obtained with standard fit from experimental data) as well as the optimized parameters obtained via numerical inverse method. The inverse method presented above, requires strong effort both from experimental and numerical point of view, anyway it allows to precisely identify the parameters of different material models. This could provide great advantages when high reliability of the material behaviour is necessary. Applicability of this method is particularly indicated for special applications in the field of aerospace engineering, ballistic, crashworthiness studies or particle accelerator technologies, where materials could be submitted to strong plastic deformations at high-strain rate in a wide range of temperatures. Adequate temperature range must be chosen in order to correctly characterize thermo-mechanical behaviour of the material.

Table 1. Model Parameters ($T_m = 1356$ K, $T_r = 233$ K).

	Johnson-Cook model					
	A (MPa)	B (MPa)	n	C	$\dot{\epsilon}_0$ (s ⁻¹)	m
Analytical (tension)	310.0	319.1	0.247	0.019	0.008	1.017
Optimized (tension)	243.7	325.1	0.140	0.018	0.034	1.066
Analytical (compression)	305.0	330.8	0.191	0.020	0.016	0.816
Optimized (compression)	304.8	279.2	0.137	0.023	0.024	0.799
	Generalized Cowper-Symonds model					
	A (MPa)	B (MPa)	n	D (s ⁻¹)	p	m
Analytical (tension)	310.0	311.5	0.232	6.563e6	5.940	1.033
Optimized (tension)	243.7	325.1	0.140	1.346e6	5.286	1.066
Analytical (compression)	305.0	338.0	0.190	1.836e6	5.181	0.840
Optimized (compression)	304.8	279.2	0.137	4.722e5	4.446	0.799

5. CONCLUSIONS

A combined experimental and numerical technique, based on an inverse approach, for material model identification was fully developed and applied to a dispersion strengthened copper. Once chosen the analytical model used to describe material behaviour (J-C and C-S were employed), several experimental tensile and compressive tests were performed at different speeds and different temperatures. Reference parameters of the material have been obtained by fitting experimental data with the analytical models. Finally material parameters have been optimized through an inverse numerical procedure: FEM simulations of all experimental tests have been performed and parameters were iteratively changed in order to reproduce the experimental curves. The procedure

described in this paper is generally valid for the identification of every material model, anyway the method must be adapted on the basis of the choice of the analytical model used as a reference. J-C and C-S models allowed, in this case, to independently optimize work-hardening, thermal and strain-rate sensitivity parameters limiting the complexity of thermo-mechanical characterization of the material.

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