Calibration of the Johnson-Cook plasticity for high strain rate regime applications

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Numerical simulation based on finite element method (FEM) technology generally accommodates the thermomechanical behaviour of metallic materials, with the advantage of greatly reducing the experimental effort required for testing and validation of components and parts. In order to obtain reliable numerical results, the calibration of material model parameters is of paramount importance, especially for high strain rate applications.

The characterization of material behaviour can be very challenging, especially if the number of parameters that govern the constitutive equations is significant. In most cases, sophisticated formulations consist of multiple parameters that require dedicated calibration from different sets of experimentally measured data. Among the phenomenology-based models, the Johnson-Cook formulation [1] is one of most widely used constitutive relations for metals subject to large strain, high strain rate, and high temperature.

In order to calibrate the material model parameters, it is necessary to evaluate each isolated contribution of the formulation and associate dedicated experimental tests to each, ranging from the classical tensile test to the less common Split-Hopkinson tensile test. Once the test data is available, a common approach to calibrating the material parameters is the numerical reverse engineering of the experimental test through the finite element method (FEM), matching the experimental curve to the numerical one.

This paper deals with the mechanical characterization of a metallic material at high strain rates. The methodology is based on the synergy of numerical tests and FE simulations, enhanced by optimization based on genetic algorithms

Experimental tests

The experimental campaign was structured as follows:

- Quasi-static tensile tests at room temperature;
- Quasi-static tensile tests at high temperatures;
- Hopkinson bar dynamic tests.

Quasi-static tensile tests were performed on a universal testing machine (see picture above), using a clip gauge and digital image correlation (DIC) to measure the specimen's elongation. Since temperature strongly influences the mechanical

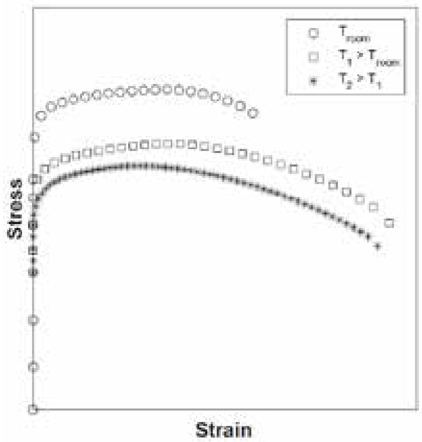

Fig. 1 - Stress-strain tensile curves at room and high temperature.

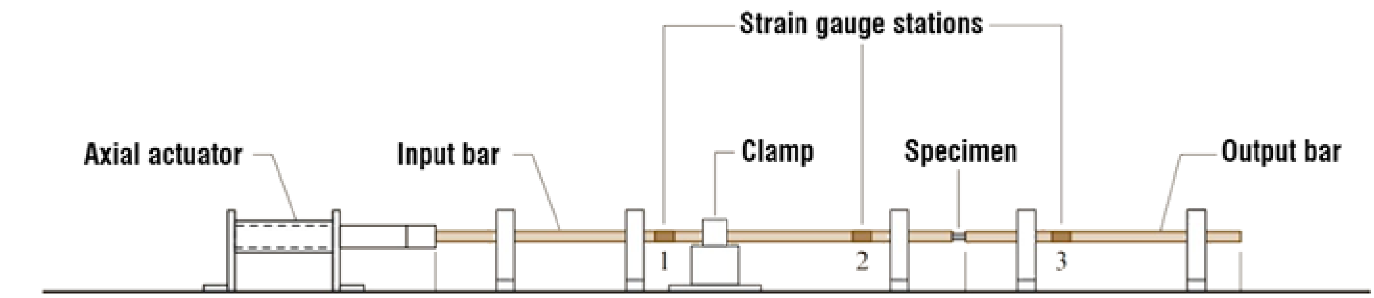

Fig. 2 - Hopkinson bar with direct-tension split.

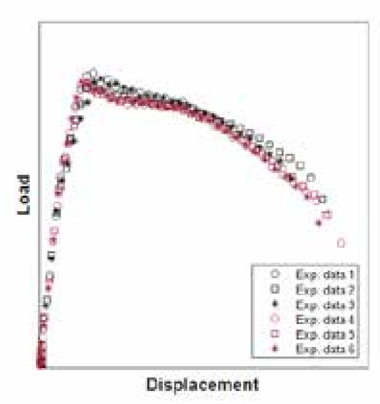

Fig. 3 - Load-displacement curves from split Hopkinson bar tests

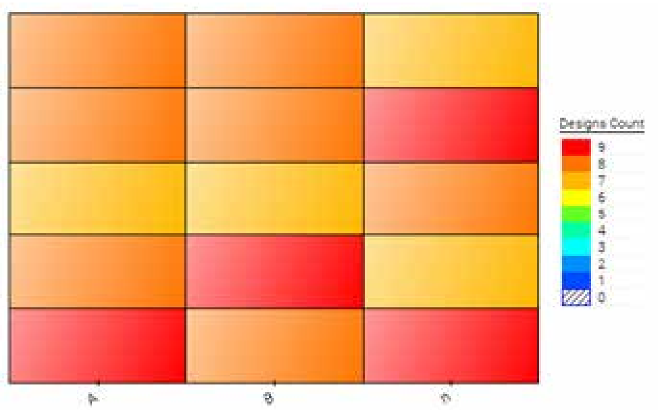

Fig. 5 - Design distribution on DOE.

behaviour of metallic materials, high temperature tensile tests were carried out to study its effect using the climatic chamber, with a thermocouple to control the temperature levels.

The engineering stress-strain curve obtained from the room temperature and high temperature tests is shown in Fig. 1.

Hopkinson bar tests allow the material behaviour to be studied in the high strain rate regime. The sample is placed between two long, thin bars (the incident and the transmitted bar). Depending on the type of impulse generated in the incident bar, it is possible to obtain tension, compression, torsion (or a combination of these) conditions. The incident and transmitted bars are designed to operate in the elastic region for the entire duration of the test. In this study, a Hopkinson bar with a direct-tension split was used, as shown in Fig. 2 [2]. The load-displacement curves obtained from the test under a high strain rate regime are shown in Fig. 3.

Material model

The material constitutive law selected for this activity is the Johnson-Cook model [1] [3] because it allows the effects of strain hardening, strain rate and temperature to be taken into account within a single formulation. According to this formulation, the equivalent stress is expressed as:

$$\sigma = (A + B\varepsilon^{n})(1 + c\ln\dot{\varepsilon}^{*})(1 - T^{*m})$$

where ε is the equivalent plastic strain, $\dot{\varepsilon}^{*}=\dot{\varepsilon}/\dot{\varepsilon}_0$ is the plastic strain rate $\dot{\varepsilon}$ with respect to the reference value $\dot{\varepsilon}_0$ and $T^{*}=(T-T_{room})/(T_{melt}-T_{room})$ is the homologous temperature considering the room temperature T_{room} and the melting temperature T_{melt}. In this formulation, the calibration concerns the parameter set A, B, n, c and m.

Numerical calibration procedure

At this point, the numerical simulation of the experimental test (Fig. 4) is performed for both the quasi-static and the high strain rate test.

The former evaluates the subset of parameters A, B and n. The latter enables us to find the refinement of the first values c and m obtained by analysing the experimental curves. All the simulations were performed using the LS-DYNA FE code, its implicit solver, and the formulation of 2D axisymmetric elements.

Fig. 4 - 2D axisymmetric FE model for Hopkinson samples.

Fig. 6 - Calibration diagram for integrating LS-DYNA into modeFRONTIER.

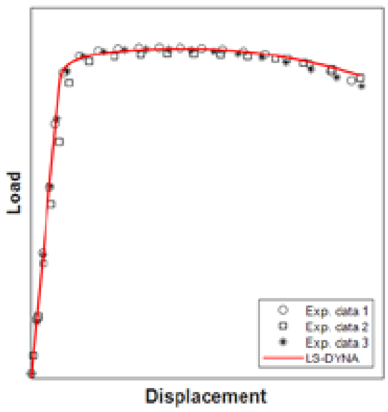

Fig. 7 - Comparison of experimental data and numerical curves for quasi-static tensile tests.

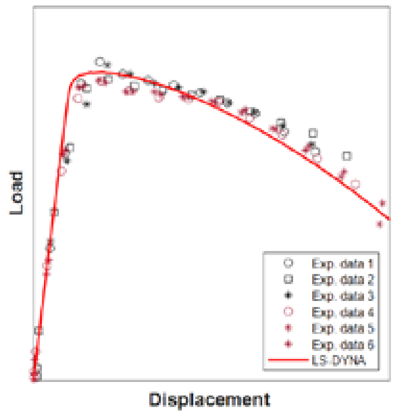

Fig. 8 - Comparison of experimental data and numerical curves for high strain rate Hopkinson bar tests.

These simulations were integrated into a fully automated procedure using modeFRONTIER optimization software. In order to minimize the correlation between parameters and maximize the distance between the generated designs, the uniform Latin hypercube (ULH) was used to create the initial design of experiment (DOE). Then, the incremental space filler (ISF) algorithm added new points to uniformly populate the input space (Fig. 5).

From the initial DOE, the generation of a new set of parameters was guided by the multi-objective genetic algorithm (MOGA) II, with the aim of minimizing the error between the experimental and numerical curves. (Fig. 6). The new set of parameters (green box) is edited within the LS-DYNA material keyword file (red box). The numerical and the experimental curves (orange box) are vectorized and compared. The difference is then minimized (blue box).

Results

From the quasi-static optimization cycle, a suitable set for A, B and n allows the tensile test to be reproduced with great accuracy in the low strain rate regime, as shown in Fig. 7. By fixing this set of values, a second calibration scheme leads to a refinement of the values for c and m obtained from the analysis of the experimental data. With the complete set of parameters, the material behaviour is fully reproduced in the high strain rate regime for the Hopkinson tests (Fig. 8).

Conclusions

This work presents the calibration of the parameters for a metallic material model, capable of reproducing plastic flows under high and low strain rates. Results from experimental tensile and Hopkinson bar tests served as the starting point for feeding the optimization scheme.

The tests, reverse-engineered using FEM and LS-DYNA's implicit solver, were incorporated into modeFRONTIER, and an optimization based on genetic algorithms produced a set of parameters on the Pareto frontier. The corresponding numerical curve were compared to the experimental data, obtaining good agreement for both the tensile and Hopkinson tests.

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