Identification of metallic material behaviors under high-velocity impact: A new tensile test

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Summary: The main objective of this paper is to present a new tensile test used to identify metallic material behaviours under dynamic loading at high strain rates. The identification methodology adopted is based on numerical-experimental optimization and uses a combined Monte-Carlo and Levenberg-Marquardt algorithm developed by the CMAO team. The basic idea of this methodology is to compare predicted final results from finite element model (like geometrical dimensions of the deformed shape, etc.) to the same experimental results measured using a macro-photographic device. The experiment set-up is a ballistic gas gun used to propel the projectile, in vacuum conditions; up to 300m/s. Numerical simulations are carried out using ABAQUS Explicit finite element code. The device used for conducting tensile testing at high strain rate encloses three principal parts: a target, a target support and a projectile. The target is designed in an attempt to ensure a useful zone of high plastic strain in tension. The paper ends by a presentation of an identification obtained by this test for two metallic materials (42CrMo4 Steel and Aluminum 2017T3) assumed to follow the Johnson-Cook strain-stress law.

INTRODUCTION

It has been widely demonstrated that the resistance of materials to applied loading depends significantly on the rate at which loads are applied. That is why a great interest has been accorded to the study of the impact at high strain rate in many mechanical domains, industrial activities (machining, sheet forming…) and transport infrastructure (aeronautics, cars …). The objective is to predict the behaviour of material under such solicitation, which explains the development of computation methods and specially finite element method. As the reliability and accuracy of obtained numerical results are directly conditioned by constitutive laws, an accurate identification of the material used is needed.

Our objective is the development of experimental tests and an identification methodology of material constitutive laws specific to test types and adapted to high strain rates. In this paper we are limited to a tensile test. Other tests (Tailor tests, shear tests, extrusion tests) have been already carried out [2] [3] [4].

Whatever the law identified by the help of impact tests, the presented identification method implies the use of three tools or steps:
- A specific test to the studied law,
- A parameterised finite elements model of the test,
- An algorithm of optimisation allowing possible minimization of the difference between the experimental data and the responses resulting from the numerical simulation.

In this paper, we present an identification of two metallic materials (42CrMo4 Steel and Aluminium 2017T3) using a tensile test. These two materials are assumed to follow the Johnson-Cook strain-stress law.

IDENTIFICATION METHOD

The identification methodology used in this paper is based on a combination between experimental and numerical techniques. This combination is piloted by a numerical code based on the Monte Carlo method and the Levenberg-Marquardt algorithm. The identification methodology used is equivalent to an optimisation technique. The basic idea of this technique is to compare predicted results (easy to measure and to control like geometrical dimensions) obtained by the help of a finite element model to the same experimental results. The difference between these two sets of parameters is minimised by the piloting code.

The identification methodology is structured into two steps. In the first step a coarse research is done by a derived Monte-Carlo random-stochastic method. In the second step, a refinement of the research is achieved using a Levenberg-Marquardt algorithm. In this latter, results provided by coarse research are used as initial condition.
The idea to use a Monte-Carlo method for this kind of identification is related to the necessity of exploring the topological space parameters law with the aim of numerical simulation. The principal steps of the Monte-Carlo algorithm are described below:

1. Introduction of the starting input data;
2. Drawing of lots which generates the sets of parameters;
3. Solving the numerical model for all the sets of parameters;
4. Evaluating the objective function of each set of parameters;
5. If the convergence criteria is not satisfied, repositioning the new start point and return to the second step.

The accuracy of the results obtained and the rate of convergence are meaningfully influenced by the choice of the objective function. The objective function represents the difference (to be optimized) between experimental and computing results. Now, according to the used methodology, two forms of the objective function can be used:

**Simple-test methodology:**

In this mythology each attempted test is considered separately and an identification is made on each one. Consequently the identification is only based on the deviation between responses of one test and the numerical model corresponding. In this case, the Euclidian norm used for the objective function is:

\[
f = \frac{1}{m} \sqrt{\sum_{i=1}^{m} w_i(j) \left( \frac{R_{EF}(j) - R_{EXP}(j)}{R_{EXP}(j)} \right)^2}
\]

where \( m \) is total number of responses;
\( R_{EF} \) is the vector of the finite element responses;
\( R_{EXP} \) is the vector of experimental responses;
\( W_i \) is the vector of the responses weights.

For more details concerning this subsection, readers are referred to reference [3].

**Multi-test methodology:**

The simple-test methodology gives as many tests of parameters as there are tests. The difficulty, thereafter, is to make the choice of the optimal set of parameters.

The alternative method recently developed is not to consider each test separately but to consider several tests at the same time and build the objective function with all the deviations between experimental and numerical responses.

In this methodology the objective function is written as follows:

\[
f = \frac{1}{m.n} \sqrt{\sum_{i=1}^{m} \left( \sum_{j=1}^{n} w_i(j) \left( \frac{R_{EF}(ij) - R_{EXP}(ij)}{R_{EXP}(ij)} \right) \right)^2}
\]

where \( n \) is the number of the considered tests.

This methodology allows to make an average of the different parameters and to minimise the deviation between each experimental parameter of all the tests at the same time an the answers given by the different numerical models.

**EXPERIMENTAL SET-UP: TENSILE TEST DEVICE**

Domains (ranges) for which we develop the methodology of identification under high speed impact implies a level of high strain rate \( (10^5 \text{ s}^{-1}) \). Because of this characteristic, a gas-gun device has been chosen to carry out impact tests. On the other hand post-mortem analyses of impacted specimens are needed.

The gas-gun has a calibre of 20 mm and a length of barrel of 1400 mm. The projectile can be propelled up to 350 m/s for a 30 gr. weight, the propulsion being provided by a mixture compressed gas nitrogen-oxygen. All tests are achieved in vacuum conditions. Projectile velocities are measured just before impact by an opto-electronic system.
This gas-gun has been initially designed for the Taylor test. Making some adaptations and taking into account some specifications it can be exploited to set-up many other tests. 

In this work we present a tensile test carried out by the help of this gas-gun. To identify the constitutive law, by such test, for studied materials, the test consists in launching a projectile into the target as showed in figure 1.

![Figure 1: the tensile test device: schematic concept](image)

The device used for conducting tensile testing at high strain rate encloses three principal parts: a target, a target support and a projectile. The target support is designed to simplify the installation of the target in the gas launcher. The projectile-support (in polycarbonate) ensures, by the help of a plastic O-ring, the sealing in the pneumatic part at the time of setting high pressure. Furthermore this later will make easy the displacement and guidance of the projectile in the barrel.

![Figure 2: The target used for the tensile test](image)

In the designing step of the target two specifications and requirements has been taken into account:

- according to the type of the studied test, the target is designed in an attempt to ensure a useful zone of high plastic strain in tension.

- ability of the designed device (target, target-support and projectile) to be simply logged in the existing gas launcher.

The experimental tests presented in this paper were done to identify the constitutive law for two metallic materials: a 2017 aluminium alloy and a 42CD4 steel. In each test the target and the projectile have the same material. Materials used for the projectile-support (polycarbonate) and the target-support (35CD4 steel) have usually the same properties and supposed to be known.

The two studied materials (42CrMo4 Steel and Aluminium 2017T3) are assumed to follow the Johnson-Cook strain-stress law. In his original form, this law has the following expression:

\[
\sigma = (A + B\dot{\varepsilon}^n)(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})(1 - T^*)
\]

Where \(\sigma, \varepsilon, \dot{\varepsilon}\) represent respectively the Von Mises equivalent stress, the equivalent plastic strain, the equivalent plastic strain rate. \(\dot{\varepsilon}_0\) is the quasi-static strain rate or a reference strain rate. \(T^*\) is a term depending
only on temperature: 
\[ T^* = \frac{T - T_0}{T_{\text{melt}} - T_0} \]
where \( T \) is the absolute temperature, \( T_{\text{melt}} \) is the melting temperature of the material and \( T_0 \) is the transition temperature.

Parameters \( A, B, n, C \) and \( m \) are material constant characteristics and represent the subject of the identification study (except the parameter \( m \) which is not considered for the identification in this work). \( A \) represents the yield stress of the material, while \( B \) and \( n \) influence the curve of work hardening. \( C \) characterises the sensitivity to the rate strain and \( m \) represents the sensitivity to the rise in temperature. In this work only the parameter \( m \) is not considered in the identification study. The used experimental means are not yet equipped with a system allowing the application and the control of thermal loading. In the numerical simulation to overcome the problem of the presence of the thermal term, we choose values of \( T_{\text{melt}} \) and \( T_0 \) ensuring a value of zero to the \( T^* \) parameter.

In the experimental part, many tests have been carried out for the two studied materials (a 2017 aluminium alloy and a 42CD4 steel). For each material we start by trying to approach approximately the critical impact speed \( i.e. \) speed corresponding to the failure. Then, we vary the impact speed for several values under the critical impact speed, but larges enough to ensure high strain and strain rate. In this study, tensile tests were performed at impacting velocity yielding from 30 m.s\(^{-1} \) to 135 m.s\(^{-1} \).

**NUMERICAL TEST MODEL**

Numerical simulations were carried out using Abaqus/Explicit [1]. The test model is an axially-symmetric as shown in figure 1. The finite element used in all simulations is the CAX4R. The mesh is refined enough and uniform in the useful tensile as well as in the contacting surfaces. A non-uniform density of mesh is used in the other regions of parts constituting the assembly of the model. In the following figure (figure 3) are presented respectively the post-mortem picture of the target and the final finite element model state.

![Figure](image)

\[ Figure \] \[ a: \text{Post-mortem picture of the specimen, b: Final state of the FEM} \]

Responses, generally geometrical dimensions, taken into account in the identification procedure depend on the studied test and the design of the specimen. In this test two responses are taken into account; the height of the tensile zone and the radius in the medium of this later.

**RESULTS AND CONCLUSIONS**

After experimental tests all impacted targets are measured in order to get the experimental response. For the studied tensile tests we have chosen the useful tensile height and the radius of the target as responses to be taken into account in the optimisation procedure of the identification algorithm. Figure 3 (a) and (b) show the two controlled responses respectively in the experimental or the post-mortem and the finite element model one. In this test (tensile test) the plastic elongation of the specimens has been considered.
We have noticed, from the finite elements model that the useful part of the target is submitted exclusively to tensile loads. Maximum values of strains are localised in the medium of the useful zone, where the ray of the target is controlled to get a second controlled response.

For the 42CD4 steel, two tests have been taken into account. A test corresponding to an impact velocity of $\mathbf{\bar{v}}\text{m.s}^{-1}$ and another of 113 $\text{m.s}^{-1}$. The identification procedure gives the following results corresponding to the parameters of the Jonson-Couk constitutive law.

<table>
<thead>
<tr>
<th>Test Type</th>
<th>A (Mpa)</th>
<th>B (Mpa)</th>
<th>n</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile test</td>
<td>17.15</td>
<td>11.52</td>
<td>0.157</td>
<td>0.00</td>
</tr>
<tr>
<td>Taylor test</td>
<td>0.22</td>
<td>14.50</td>
<td>0.1</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Tabular 1: results of the identification of the 42CD4 steel by the tensile test, comparison results obtained by Taylor test.

Fig. 4: Identified Constitutive law of the 42CD4 steel: comparison between Taylor test and tensile test

To identify the 2017 aluminium alloy, three tests have been taken into account. A test corresponding to an impact speed of 4 $\text{m.s}^{-1}$, a second one to 0 $\text{m.s}^{-1}$ and a third one to 7 $\text{m.s}^{-1}$. The identification procedure gives the following results of the identified parameters.

<table>
<thead>
<tr>
<th>Test Type</th>
<th>A (MPa)</th>
<th>B (MPa)</th>
<th>n</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile test</td>
<td>5.30</td>
<td>31.400</td>
<td>0.27</td>
<td>0.025</td>
</tr>
<tr>
<td>Taylor test</td>
<td>3.00</td>
<td>31.550</td>
<td>0.2</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Tabular 2: results of the identification of the 2017 aluminium alloy by the tensile test, comparison results obtained by Taylor test.

Fig. 5: Identified Constitutive law of the 2017 aluminium alloy: comparison between Taylor test and tensile test
One remarks, for the two identified materials, a slight difference between results obtained with the tensile test and those obtained by the Taylor test. This difference can be explained by the presence of the friction phenomenon, between the contacting surfaces, in the Taylor test. Complementary explanations will be given in a study (actually in progress) for a multi-test approach by the methodology of identification used and presented in this paper.

In this paper we have presented a dynamic tensile test to identify two metallic materials; a 2017 aluminium alloy and a 42CD4 steel. The presented results show, the facility and the accuracy of the used methodology to identify materials. As it has been shown, in other tests, obtained results of identification are specific to the type of the considered test. Thus a strategy to choose the appropriate test or to take into account several tests is needed to get accurate results of identification.

References: