IDENTIFICATION OF DYNAMIC BEHAVIOUR LAW PARAMETERS FOR METALLIC MATERIALS USING TAYLOR IMPACT TEST

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This paper presents an identification procedure of dynamic behaviour law parameters based on Taylor impact test. Experiments are done using a compressed gas gun facility allowing to obtain high strain rates for metallic materials under impact. The evaluation of the experimental results is based on the measure of the final deformed shape by a macro-photographic device. An identification program based on a combined Monte-Carlo and Levenberg-Marquardt algorithms performs a minimisation between experimental final geometry and the numerical one provided by the corresponding FE model. This algorithms combination, implemented using the C++ language in the home made identification program called ***Identif***, gives the numerical values for the constitutive parameters of the identified laws. An application for an aluminium alloy shows the efficiency and robustness of the proposed procedure.

1. INTRODUCTION

The characterisation of the materials behaviour under large dynamic loads becomes more and more important in many present applications. This field has received much attention over the last years and efforts were done in order to develop numerical and experimental identification techniques for the behaviour of the metallic materials.

A structure under dynamic loads can sustain, in function of loading nature, large variations in its behaviour, from plastic deformation to fracture. The dynamic character of these solicitations calls the use of viscoplastic laws, damage and fracture criteria taking into account the specifically parameters in fast dynamics: strain rate, temperature, crack speed propagation etc. One can, integrating these laws and criteria into numerical codes, predict the structure behaviour and identify the dangerous areas from security point of view. The applications area are a very large one, from industrial field with high speed machining or car's crash to military field for target's perforation or explosives effect.

Several problems are to be solved for numerical modelling of dynamically loaded structures: the choice of a good mathematical model, the identification of

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the numerical values of the constitutive parameters of the employed behaviour laws and fracture criteria and the availability of an analysis code which integrates these laws and criteria.

In this paper we propose, as solution for the second problem presented above, an identification technique, using Taylor impact tests, for determining the numerical values of behaviour law parameters used for numerical simulation of metallic structures subjected to dynamic loads. Two main components of this technique, involving original contributions of the authors, are presented here: the experimental framework of our laboratory and the parametric identification program, based on an original combination between a Monte-Carlo algorithm and the Levenberg-Marquardt algorithm. The experimental tests presented here are intended for identification of the Johnson-Cook law [1] whereas the parametric identification program is suitable for any behaviour law or fracture criteria.

Further, the paper is structured as follows. Following this introduction, the second section presents the experimental framework, the main characteristics of the gas gun, Taylor impact test description and the procedure for post-impact exploitation of the results. The theoretical basis and the features of the parametric identification program are detailed in the third section. In the fourth section an example of parametric identification for an aluminium alloy proves the efficiency and robustness of the proposed identification procedure. In the last section one concludes on the efficacy of the procedure and the future prospects are presented.

2. EXPERIMENTAL SET-UP. TAYLOR IMPACT TEST

The experimental set-up of the impact laboratory from National Engineering School from Tarbes is intended for studying the dynamic behaviour of metallic materials in order to complete the virtual design platform for rapid thermo-mechanical high transformations. In this respect, the main objective of the experimental tests is to supply to the identification procedure so called "experimental responses" used further for finding the numerical values for the constitutive law parameters.

From strain rate point of view, $\dot{\varepsilon}$, the impact tests that we are able to conduct in this laboratory are situated between the tests performed with Hopkinson bars ($\dot{\varepsilon} = 10^2 \ldots 10^3 \mathrm{s}^{-1}$) and the ones realised using explosives ($\dot{\varepsilon} > 10^6 \mathrm{s}^{-1}$). The remained range, from 10^3 to 10^6 s^{-1}, specifically for machining, crash and impact phenomena, corresponds to the Taylor impact test presented bellow in this section.

The impact tests are performed using a compressed gas gun facility (Fig. 1) having the following mains characteristics:

- calibre: 20 mm;
- barrel length: 2 m;
- projectile speed range: from 30 up to 350 m/s for a 30 g mass;

- energy supply: nitrogen-oxygen gas compressed up to 190 bar;
- speed measurement device based on LASER barriers.

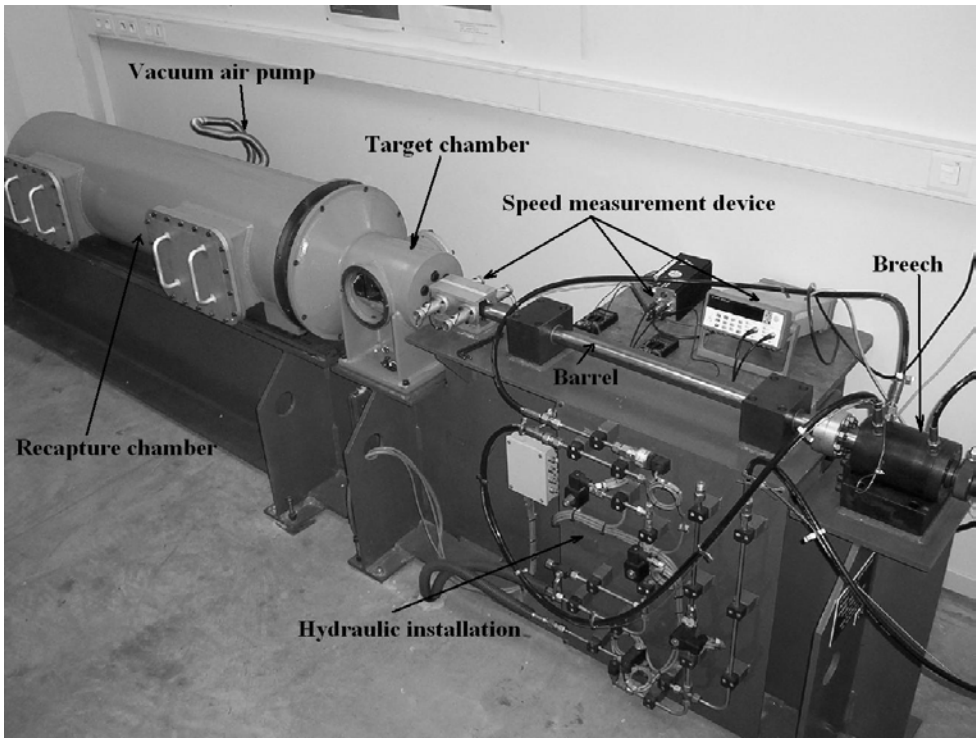
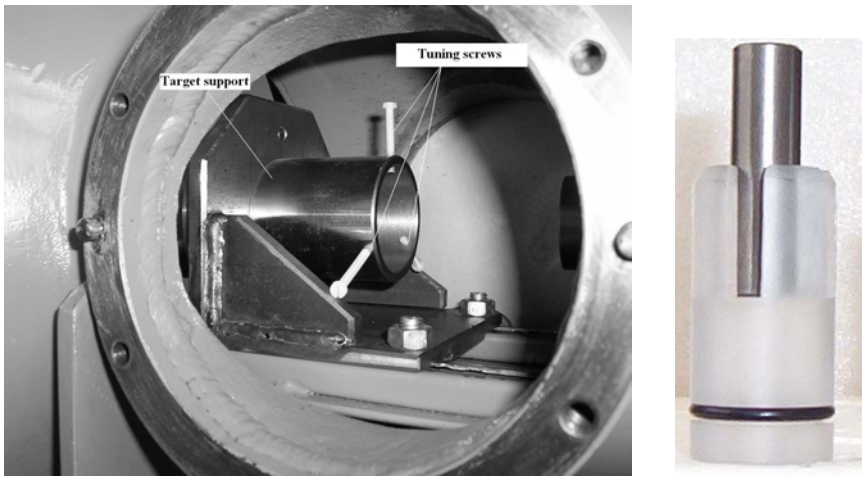


Fig. 1 – Compressed gas gun facility.

The gas-gun calibre being 20 mm, for launching projectiles with a smaller diameter, a polycarbonate sabot are used for equipping these ones (Fig. 2b). The sabot functions are to ensure the tightness behind the projectile through an elastic joint and to guide the projectile displacement along the barrel. The installation of the target into the target chamber is ensured by a target support (Fig. 2a) equipped with six tuning screws (the three ones placed in the front of the target support being visible on the image). Turning in and out these screws one can provide the alignment of the target with the projectile.

The behaviour of the sabot during the impact is a very randomly one involving partial disruption, plastic deformations etc. making difficult the numerical modelling. For avoiding the integration of the sabot in the numerical models of the impact tests, two perpendicular notches were done as one can observe on Fig. 2b. In this way a controlled breaking of the sabot is obtained, vanishing its influence on the projectile during the impact. The energy contribution

of the sabot is considered in the numerical model adding the corresponding mass behind the projectile.



a) b)

Fig. 2 – a) Target support chamber; b) projectile equipped with sabot.

The exploitation system of the experimental results obtained follow-up the impact tests is based on post-mortem analysis of the impacted specimens. This analysis concerns two main aspects: a checking about material integrity for pointing out the damage and fracture and a dimensional measuring for getting the deformed shape. In case of the tests intended for dynamic viscoplastic flow law identification, only the impacted specimens without any damage are considered for dimensional measuring. For this one, a macro-photographic procedure is employed using a digital camera Nikon D1X equipped by a 60 mm 1:2.8 D macro lenses.

The technical feature of this camera allows to obtain a digital image of 4028×2648 pixels having a spatial resolution of $5.9 \cdot 10^{-3}$ mm for a macro ratio 1:1. The captured images of the deformed specimens are treated by the *ImageAnalyser* software [2] (see the main windows on Fig. 3) able to built a 2D reference system in order to associate for each image pixel the real coordinates in millimetres. So, applying some filters for improving the image quality, the deformed shape of the specimen is obtained and converted into a 2D curve.

The Taylor impact test was the first impact test developed by Taylor [3] and Whiffin [4] for the identification of metallic material behaviour under dynamic loads It concerns, as we will see further, the dynamic compression behaviour. Since, many authors used this test for identify the constitutive parameters of complex behaviour law as Johnson-Cook, Zerilli-Amstrong or Simo models.

The principle of this test is to impact a cylindrical specimen either to another identically one (symmetric Taylor test, see Fig. 4a) or to a rigid target (direct

Taylor test, see Fig. 4b). The advantage of the first version of this test concerns the friction effects on impact faces. An impact on symmetrical surfaces vanishes the friction influence but in the same time, this version is more difficult to implement because of problems with axis alignment of two specimens. On the other side, the direct version is cheaper to implement (the target can be used several times), is more easy to obtain a perpendicular impact but for the friction effects one must search a solution, as the oiling of the impact faces.

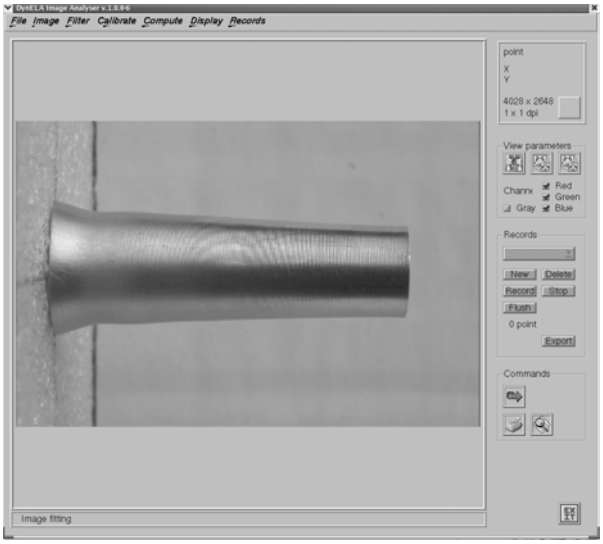


Fig. 3 – The main windows of *ImageAnalyser* application.

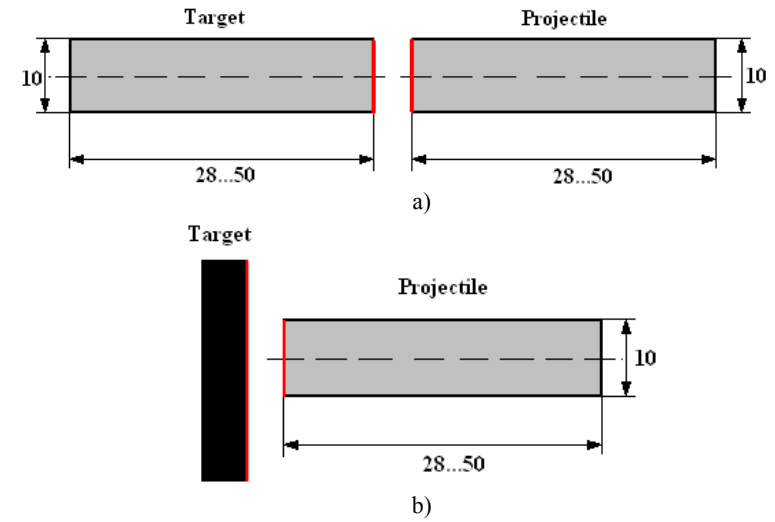


Fig. 4 – Taylor test schemes: a) symmetric test; b) direct test.

In both cases, Taylor test leads to large strain, with very high strain rates, for the impacted specimen ends. The deformed shape of the specimens (the left side of Fig. 5) provides the experimental responses, such final length, final radius of the impacted face and intermediate radius along the specimen. These responses, in corroboration with the corresponding numerically ones (the right side of Fig. 5), are used as input for the parametric identification program, as presented in the next section.

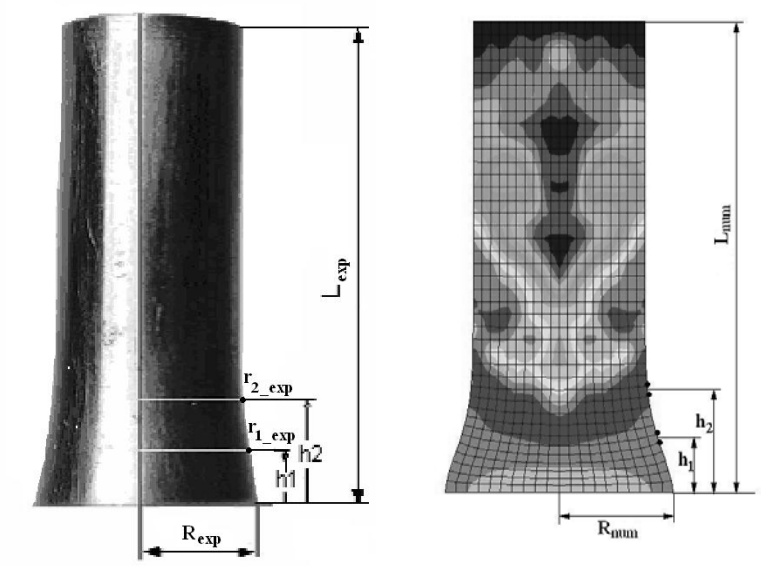


Fig. 5 – Taylor test responses: experimental (left) and numerical (right)

Function of tested material, impact speed ranges from 50 to 500 m/s and one recommend choosing an optimal ratio length/diameter for avoiding plastic deformations for the bottom of the specimens [5].

3. PARAMETRIC IDENTIFICATION PROGRAM

The parametric identification, as a significant scientific problem, began since a few tens of years when ones wanted to determinate accurately the numerical values for the parameters of the models. One of the approaching in this field is given by the concept of the inverse problem for the identification of the material behaviour. The formulation of this concept, retained for our works, was the one proposed by Astrom and Eykhoff in 1971 [6] which consist to minimize, by an iterative process, an objective function based on the difference between a vector of experimental data and the same data obtained analytically.

Obviously the formulation of the parametric identification as an optimization problem is unanimously accepted. The mathematical formulation of the objective

function is based, in almost all papers, on the difference between the vector of the experimental results and the results given by simulation. But the optimization method chosen for minimizing the objective function depends on the author. Two mainly classes of algorithms are used for this aim: exploring ones as Simplex algorithm or Monte-Carlo method and descent algorithms as the maximum slope method, the combined gradient method, the Gauss-Newton algorithm or the Levenberg-Marquardt algorithm [6, 7, 8].

The main idea, during the development of the identification procedure presented here, was to have a very general method suitable for determining the parameters of various behaviour laws, in a large range of mechanical application. So it was taken into account the variable nature and number of the identified parameters, the possibility to identify only a part of them if this is desirable and the possibility to take into account various experimental and numerical outputs and the control given to the user on the procedure. The necessity to identify the same parameters starting from several different tests or several input data for the same test (different impact speeds for example), in order to extend the application area for identified laws, was also one of our work criteria for developing this procedure.

Taking into account all the considerations presented above, the identification program was built as a combination between an exploring algorithm and a descent one, on two stages:

1. In a first step, a coarse research by a derived Monte-Carlo random-stochastic method is done;

2. Then, a refinement of this research is achieved by the Levenberg-Marquardt algorithm, using the results provided by coarse research as initial condition.

So, the advantages of both algorithms are exploited: the capability of the first one to explore the parametric space in order to lead the research in the neighbourhood of the global minimum and the convergence speed of the second one for obtaining the most accurate set of parameters.

Before presenting the numerical implementation of this combination into the identification program, some considerations about the objective function formulation are essential. As already mentioned, the most used mathematical formulation of the objective function is based on the difference between the vector of the experimental results and the results given by simulation and this one we chosen too. Concerning the norm of this difference, the influence studies [6] shown that the fastest convergence corresponding to the Euclidean norm and thus the mathematical formulation of the objective function is:

$$f = \frac{1}{m}\sqrt{\sum_{j=1}^{m} w_r[j]\left(\frac{r_{EF}[j]-r_{\exp}[j]}{r_{\exp}[j]}\right)^2}\ , \tag{1}$$

where: m is the total number of the responses; $r_{EF}[j]$ is the vector of the simulated responses; $r_{\exp}[j]$ is the vector of the experimental responses; $w_r[j]$ is the vector of the responses weights.

The vectors of the simulated and experimental responses called above, in Taylor test case, are composed by the measured lengths on the deformed projectile as presented on Fig. 5.

In order to extend the validity of the identified parameters over a wider range of strain rates, a so-called multi-speed strategy was developed for taking as experimental input data responses corresponding to several impact speeds. In this case, the mathematical formulation of the objective function becomes:

$$f = \frac{1}{m \cdot n} \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{m} w_r[i,j] \left(\frac{r_{EF}[i,j] - r_{\exp}[i,j]}{r_{\exp}[i,j]} \right)^2} , \tag{2}$$

where n is the total number of the tests.

The parametric identification starts with the Monte-Carlo algorithm, based mainly on drawings of lots in order to generate quasi-random values for the parameters to identify, in a range defined by the user. The main steps of this algorithm are:

1. Introduction of the input data;
2. Drawing of lots generating the sets of parameters;
3. Solving the numerical model for all the sets of parameters;
4. Evaluation of the objective function for each set of parameters;
5. If convergence criteria is not reached repositioning the new starting point and go back to step 2.

These steps represent one Monte-Carlo iteration, several iterations being in the most of cases necessary for reaching the satisfaction criteria. As satisfaction criteria here one designs the value imposed by the user for the objective function for the end of this algorithm or the maximal number of iterations (imposed for ensuring the stop in case of a non-convergent procedure). On Fig. 6 one can see, for a simple benchmark test run during the validation program, a graphical illustration of Monte-Carlo algorithm running. For an identification of two parameters (C and m) using two responses (Radius and Length), one can observe the displacement of 4 iterations Monte-Carlo composed by the corresponding drawings of lots (top graph) and the motion of the cloud of the corresponding responses toward the position of the experimental responses (bottom graph).

For the implementation of this Monte-Carlo algorithm, two main problems, related to drawing of lots, arisen: the choice of the number of parameters sets for a good coverage of the space corresponding to each situation and the choice of a good random generator algorithm suitable to generate good parameter sets.

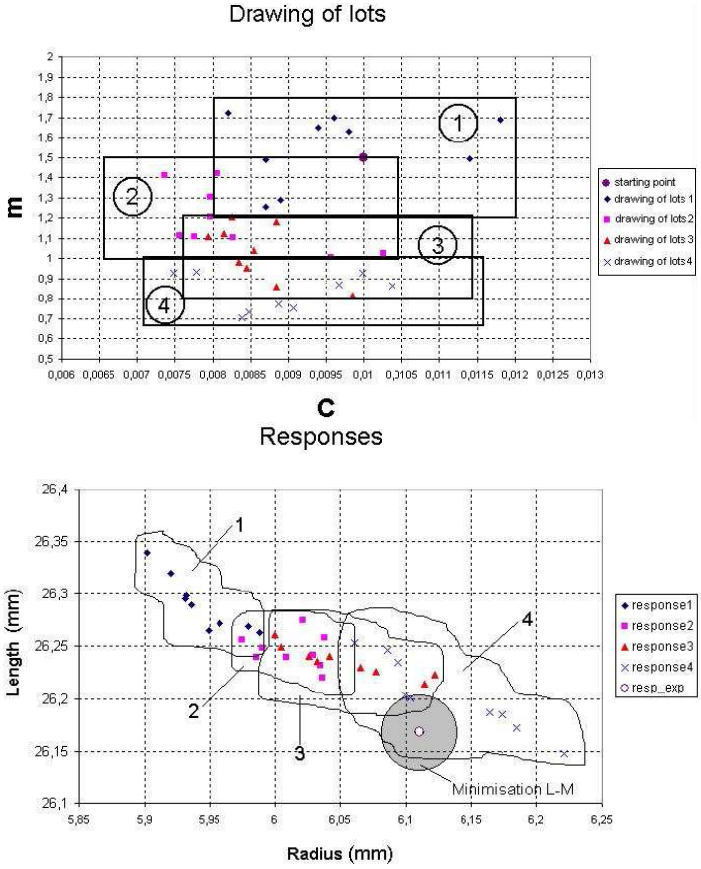


Fig. 6 – Example of Monte-Carlo algorithm running.

Therefore, for the first one, we have considered, for the number of drawing of lots N, a simple relation giving a sufficient coverage whatever the number of parameters is. This one also takes into account computation cost. Therefore N is given by:

$$N = 3^n , \tag{3}$$

where n is the number of parameters. For each parameter to be identified one will have N drawn values and the combination of those values for each parameter will give N sets of parameters. The number of drawing of lots proposed by can be considered insufficient for a good coverage of the space, for this reason we implement another mechanism which ameliorates the algorithm: the resumption of the drawing of lots if the convergence criteria of an Monte-Carlo iteration is not reached (step 5 of the Monte-Carlo algorithm). For the success of this mechanism we need to solve the second problem mentioned above, i.e. to find a good random generator.

In fact a computer is a deterministic machine with states perfectly reproducible and, in theory, foreseeable: being given a certain entry (called seed further), the same computer always produces the same result as output. To exceed this violation of the random generation and to avoid in same time to enter a value of the seed in an interactive way, one uses the clock of the system to set this value.

Once the satisfaction criterion for the Monte-Carlo algorithm fulfilled, one passes to the refinement of research by the Levenberg-Marquardt algorithm [9, 10], which derives from the resolution of a non-linear equation system.

The basic idea is to search the vector $\underline{x}$, solution of the non-linear system below:

$$\underline{r_{EF}}(\underline{x}) = \underline{r_{\exp}} \,. \tag{4}$$

This one represents in fact the system corresponding to the parametric identification (in our case the unknown vector $\underline{x}$ is the vector of the parameters to be identified). After the development in Taylor series, around $\underline{x}^{(k)}$, of the vector $\underline{r_{EF}}(\underline{x})$, we obtain the final form of the system (4) giving the new approximation of the optimal parameters:

$$\left(\underline{\underline{J}}^T J + \lambda_{LM}\, \underline{\underline{I}}\right)\left(\underline{x}^{(k+1)} - \underline{x}^{(k)}\right) = \underline{\underline{J}}^T \left(\underline{r_{EF}}\left(x^{(k)}\right) - \underline{r_{\exp}}\right), \tag{5}$$

where $\underline{\underline{I}}$ is the identity matrix, $\underline{\underline{J}}$ is the Jacobian matrix containing the partial derivatives of the vector $\underline{r_{EF}}(\underline{x})$ and λ_{LM} is the characteristically parameter of the Levenberg-Marquardt algorithm used to drive the stabilization of the minimisation.

Stabilization is carried out using an under-iteration procedure. For each iteration, one calculates with respect to (6) the new approximation for the parameters to be identified, $\underline{x}^{(k+1)}$. The new value of the objective function is then evaluated. If this one is smaller than the previous value, the iteration is convergent and one passes to following iteration decreasing the value of λ_{LM}. On the other hand, if the k iteration diverges, one starts again this one after increasing the value of λ_{LM}. Successive increases of the λ_{LM} parameter are done until a convergent iteration is reached.

The first approximation for the parameters to be identified with the Levenberg-Marquardt algorithm is provided by the best parameters (the last ones) given by Monte-Carlo algorithm thus carrying out the link between the two parts of the identification procedure.

The satisfaction criterion of the Levenberg-Marquardt algorithm is reached when the imposed value for the objective function is obtained or when the difference between the values of the objective function corresponding to the last two approximations of the parameters is smaller than an imposed amount (there is

no more minimization). Once this criterion is satisfied we obtain the final set of parameters for the identification procedure.

The numerical implementation of this combination of identification algorithms, that we proposed, was done in a home made C++ program called ***Identif*** [11, 12, 13]. For launching an identification, the user must introduce, using the graphical interface shown on the middle of Figure 7 the input data for the parameters to identify (initial values, imposed variations etc.) and for the responses taken into account (experimental values, some information for the extraction of the numerical values etc.). The accuracy of the identification is also tuned using this interface. Besides the integration of the algorithms presented above, this program performs some other tasks:

- management of the input data,
- launch of the numerical simulations for the test model, editing Python scripts,
- extraction of the numerical results from output database after simulation using Fortran or Python procedures,
- link between Monte-Carlo and Levenberg-Marquardt algorithms.

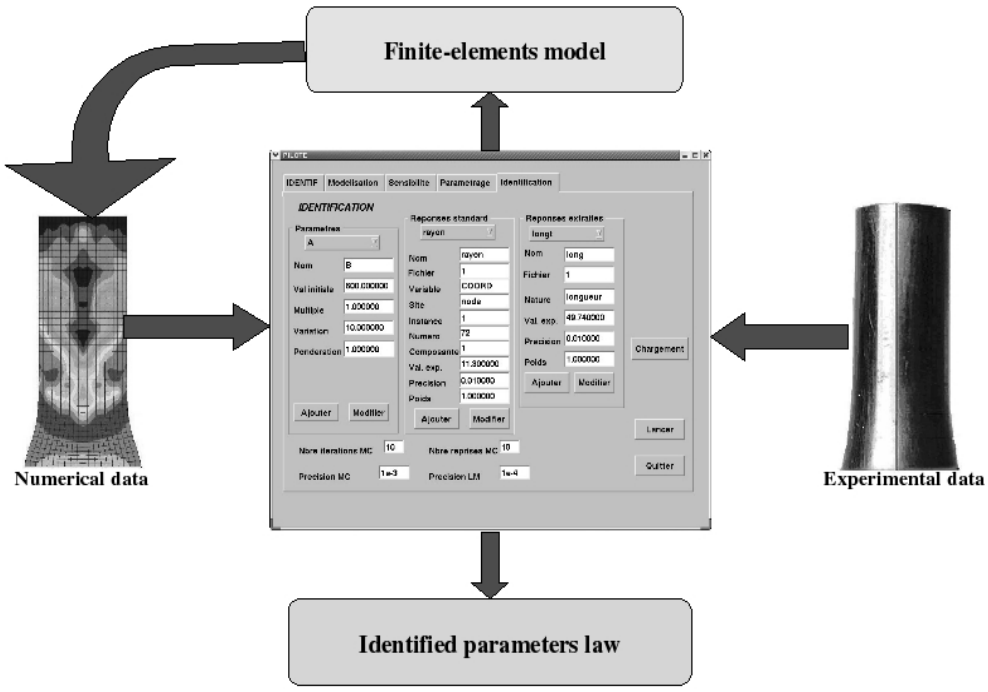


Fig. 7 – ***Identif*** running scheme.

The working of the identification program is illustrated on Fig. 7:

1. The user introduces the experimental input data;
2. ***Identif*** launch the finite-elements model;
3. Numerical responses are determined;
4. Objective function is computed in ***Identif***;
5. Steps 2, 3 and 4 are repeated until the satisfaction criterion is fulfilled;
6. Finally, identified parameters law are obtained.

The main advantages of this program results from its flexibility, the user can handle the identification process as he wants by choosing the variation of the input values for the parameters to identify, the accuracy and maximal number of iterations for Monte-Carlo algorithm, obtaining in this way the optimal balance between algorithms. For example, in case of an identification of a high number of parameters, is indicated to give a large "freedom" of parameters to vary and to limit the Monte-Carlo iterations number, very expensive in term of computing time in this case. It's depends on each case, function of FE model size, the number of parameters to identify, the number of responses taken into account etc, the choice of the initial program tuning.

4. IDENTIFICATION EXAMPLE

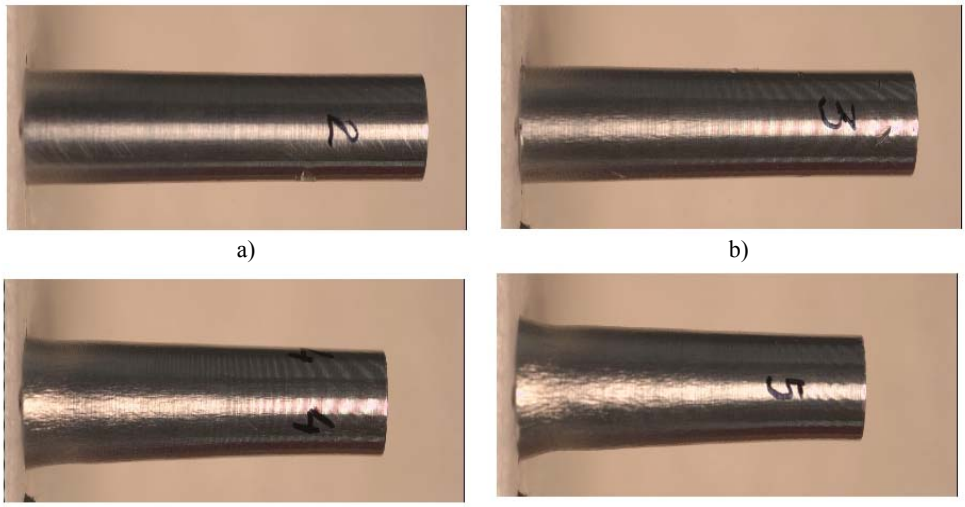
In this section we present, as an application, the identification of Johnson-Cook parameters laws for an aluminium alloy used in aeronautical structures manufacturing, A-U4G1 T3, using direct Taylor tests achieved in our laboratory [14].

We recall here the formulation of the Johnson-Cook law:

$$\sigma = \left[A + B\left(\bar{\varepsilon}^{p}\right)^{n} \right] \left[1 + C \ln \dot{\varepsilon}^{*} \right] \left[1 - T^{*m} \right]. \tag{6}$$

In (6) σ represents the equivalent Von Mises stress, $\bar{\varepsilon}^{p}$ is the plastic strain, $\dot{\varepsilon}^{*} = \dot{\bar{\varepsilon}}^{p} / \dot{\varepsilon}_0$ is the normalized equivalent plastic strain rate, $T^{*} = \dfrac{T - T_0}{T_{melt} - T_0}$ is the homologous temperature. The constants *A, B, n, C* and *m* are the empirical parameters of the law to be determined. *A* represents the yield stress, *n* and *B* are the hardening parameters, *C* concerns the influence given by the strain rate and *m* represents the sensibility with the temperature.

For launching the identification, five direct Taylor tests were performed using projectiles made from A-U4G1 T3 alloy, having the initial length of 50 mm and the diameter of 10 mm. The first test, with an impact speed of 102 m/s, was not taken into account due to the small plastic deformation obtained. The impact speeds and the experimental responses the 4 others tests are given in Table 1 and the images of the deformed shapes are shown on Fig. 8. Note that the two intermediate radius (r_1 and r_2) correspond to $h_1 = 10$ mm and $h_2 = 20$ mm (see also Fig. 5).



a) b)

c) d)

Fig. 8 – Taylor projectiles after impact: a) $V_2 = 133.80$ m/s; b) $V_3 = 155.71$ m/s, c) $V_4 = 230.00$ m/s; d) $V_5 = 248.03$ m/s.

Abaqus Explicit [15] numerical models were built for each of the tests, using the properties of the mentioned aluminium alloy: the mass density $\rho = 2784\ \text{kg/m}^3$, Young modulus $E = 74.3$ GPa and Poisson coefficient $\mu = 0.33$. A convergence study for meshing the projectiles was achieved.

Table 1

Experimental responses for Taylor tests

Test	Speed [m/s]	L [mm]	R [mm]	r_1 [mm]	r_2 [mm]
2	133.80	47.56	5.37	5.28	5.14
3	155.71	46.74	5.50	5.35	5.16
4	230.00	42.80	6.32	5.61	5.39
5	248.03	41.42	6.78	5.73	5.49

Table 2

Identified Johnson-Cook law parameters

	A [MPa]	B [MPa]	n	C	m	f
Start values	360	316	0.28	0.0188	1	
Test 1	344	674	0.316	0.0110	0.92	0.00664
Test 2	327	661	0.271	0.0135	0.94	0.00358
Test 3	379	557	0.293	0.0150	0.95	0.00697
Test 4	388	501	0.278	0.0169	0.94	0.00966
Multi-speed identification	321	672	0.226	0.0092	0.97	0.0143

Two identification strategies were applied this time: single test identification for each impact speed and the multi-speed identification considering whole experimental responses. The results of both strategies are shown on Table 2 and the hardening curves are figured on the graphic from Fig. 9.

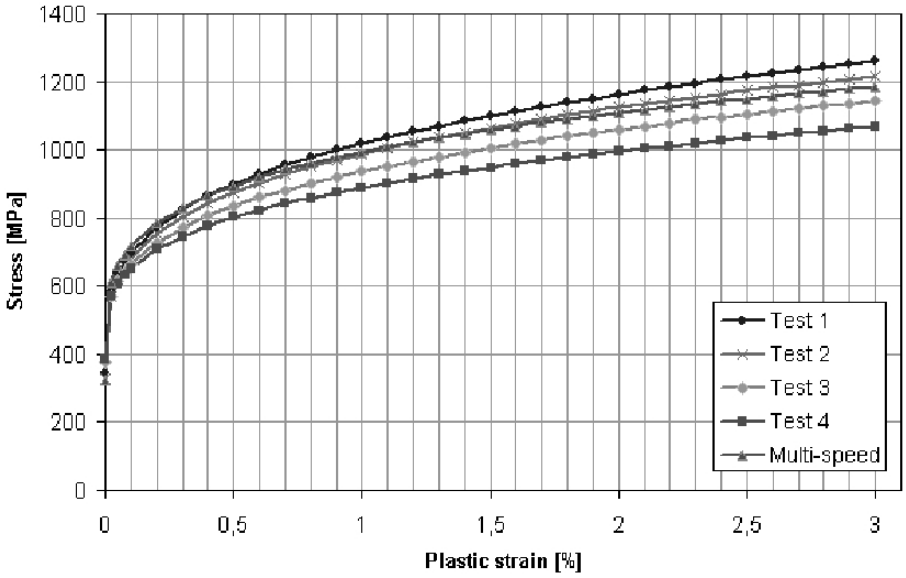


Fig. 9 – Hardening curves of the identified Johnson-Cook law.

As expected, in case of single-test identifications, we found different values for the same identified parameters, corresponding to the different impact speeds. Actually this justify the need of a multi-speed identification in order to obtain a parameters set able to characterize the behaviour of the material over the whole impact speed range. Of course, it's about a compromise and this is illustrated on the graphic from Figure 8 were the hardening curve corresponding to multi-speed identification is located between the others. So, one can considerate as final results of identification in this case, the parameters set corresponding to multi-speed identification.

5. CONCLUSION

A parametric identification procedure, consisting from numerical and experimental tools, was developed in order characterise the behaviour of metallic materials under dynamic loads. Taylor impact tests were performed in our laboratory, using a gas-gun facility, in order to obtain experimental responses for this procedure. A C++ identification program was developed in order to integrate a combination of two minimisation algorithms, Monte-Carlo and Levenberg-

Marquardt, and to achieve the identification of numerical values for behaviour law parameters ensuring the connection with the FE codes employed for modelling the impact tests. The results presented in this paper an application on an aluminium alloy prove the efficacy and the robustness of the identification procedure. The experimental framework of this procedure is to be ameliorated by new devices intended to allow more accuracy for experimental responses and to obtain other ones than only the deformed shapes of the specimens.

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