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A new dynamic test for the identification of high speed friction law using a gas-gun device

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Abstract. In the framework of metal forming, which involves high speed loads, the determination of the friction law is one of the most essential topics. Especially for Finite-element simulation the development of innovative local friction laws improves the quality of the numerical results. One of the most critical point reside in the accuracy of the identification of the governing friction law parameters. A new experimental test is based on conical extrusion. The idea is to launch a cylindrical projectile into a target provided with a conical bore prolonged with a cylindrical one. The projectile is stopped by friction forces occurring at the interface between those materials. After impact the length of extrusion is taken into account for friction law identification. The experimental set-up used is a ballistic gas-gun device capable to launch the projectile, in vacuum conditions, up to 300 m/s. The experiment is simulated by a numerical model using ABAQUS Explicit finite-element code. This code allows the implementation of various user friction laws through a FORTRAN subroutine. In order to obtain accurate results, the viscoplastic constitutive law used for both materials (projectile and target) was previously experimentally identified. The friction law identification uses a combined Monte-Carlo and Levenberg-Marquardt algorithm which provides a very precisely set of parameters law. The test presented in this paper involves two metallic materials: steel 42CrMo4 for the target and aluminum 2017 for the projectile. The friction law for the pair of materials used was validated using experimental test at different speeds of impact (149 up to 235 m/s) and the results are quite good proving a good identification of the friction law parameters.

1 Introduction

The identification of the friction laws for high speed applications which involve contact moving surfaces is one of the priority for a good simulation of the phenomenas through Finite Element Method (FEM). Along with the parameters of the behavior laws of the materials, the friction laws parameters are used in all FEM software as input data accordingly to the mechanical and thermal loads.

The laws of friction generally express the components in the contact plane of the vector "tension of contact" according to the other local parameters (normal component or "contact pressure", relative slip rate, temperature, degree of wear, etc.). Their form is based on the way of defining the criterion of threshold between "reversible" behavior in shearing and the "non-reversible" behavior, and on the law of flow beyond this threshold.

From the law of Amontons-Coulomb, with threshold characterized by a coefficient of constant friction, many authors introduced other thresholds by analogy with the constitutive behavior. Thus, one can use laws of "plastic" friction type (example: law of Tresca) associated laws of "standard" flow, laws of the "viscoplastic" type taking into account the relative slip rate (law of Norton, regularized to avoid the numerical difficulties, in particular by Kobayashi [3]). More recently, Ponthot [6] proposed a formalism with law of flow non-associated, integrating thresholds of friction, slip rate, viscosity and variables of heredity representing wear.

Other authors propose laws in experimental matter, valid in a field speeds or a particular application. Thus, Kato [2] in the case of the contact tool-chip in metal forming, Montgomery [4] in the field of ballistics. For our experimental test we used the Coulomb law in the first stage for proving the efficiency of the test and as a starting point for implementation, according to the results, of another law like the exponential one, which allows to take into account a statical parameter, a kinetic one and the slip rate.

The experimental difficulty in the friction law identification is related on the very localized character of the phenomenon to identify and to practical impossibilities of the direct measurement of the parameters such as the interfacial temperature and contact stress. One cannot thus free oneself from a certain "noise" because of the parameters not taken into account, and the quality of the experimentation depends directly on the importance of this noise. So the basic principles of the design of the experimental device are:

- adopting a metrology as "close" as possible in order to limit the noise and to control the boundary conditions of the smallest-scale possible model (often, one is led to use only one metrology "post-test", in particular when the speeds are very high);
- keeping a coherent scale with the use of the identified laws (size of the finite elements in general).

Respecting all these principles, in this paper we present the identification of a Coulomb friction law for a pair of materials (steel 42CrMo4 - aluminium 2017), in the range of speed for 150 up to 235 m/s, through a new experimental test.

2 Basics on the identification method

The identification of the friction law was achieved using a method developed by CMAO team based on a combination between Monte-Carlo and Levenberg-Marquardt algorithms. A detailed presentation of this method was made in [5]. The basic idea of this procedure is to compare predicted final results from FE model (like geometrical dimensions of the deformed shape, etc.) to the same experimental results measured by a macro-photographic device. The difference between these two sets of results is minimized by the above-mentioned algorithms combination leading to the identified parameters law. So the identification procedure is structured in two steps. In a first step, a coarse research by a derived Monte-Carlo random-stochastic method is done and then, in the second step, a refinement of this research is achieved by the Levenberg-Marquardt algorithm, using the results provided by coarse research 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 of the parameters law with the aim of numerical simulation. The principal steps of the Monte-Carlo algorithm are described below:

1. Introducing of the 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 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 the second step.

The choice of the objective function has a significant influence on the identification results and the rate of convergence. The most used formulation of the objective function in the parametric identification field is based on a norm of the difference between the vector of the experimental results and the results given by simulation. Many authors improved this formulation taking into account weights on the results, the kind of the norm or introducing the experimental errors. One can obtain a general expression of the objective function in the following form:

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

where:

- m is the total number of responses;
- r_{EF} is the vector of the simulated responses;
- r_{exp} is the vector of the experimental responses;
- w_r is the vector of the responses weights.

Following the evaluation of the satisfaction criterion for the Monte-Carlo algorithm, one passes to the refinement of research by the Levenberg-Marquardt algorithm. The Levenberg-Marquardt algorithm [7] derives, like the Gauss-Newton method, from the resolution of a non-linear equation system. We mentioned here the Gauss-Newton method because the Levenberg-Marquardt algorithm constitutes a stabilized version of this one. In this case the vector of the parameters to be identified, \underline{x} , results from an iterative process managed by the system equation:

$$\left(\underline{J}^T \underline{J} + \lambda_{LM} \underline{I} \right) \left(\underline{x}^{(k+1)} - \underline{x}^{(k)} \right) = \underline{J}^T \left(\underline{r}_{EF} \left(\underline{x}^{(k)} \right) - \underline{r}_{exp} \right) \quad (2)$$

where \underline{I} where is the identity matrix, \underline{J} is the Jacobian matrix containing the partial derivatives and λ_{LM} is the numerical parameter characteristic of the Levenberg-Marquardt algorithm used to drive the stabilization of the Gauss-Newton method. 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 objective function has the same form as for Monte-Carlo algorithm and the satisfaction criterion is reached 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).

This identification procedure has been implemented in C++ in the *Identif* program. Besides the two mathematical models, corresponding to Monte-Carlo and Levenberg-Marquardt algorithms, this program achieves some tasks: the introduction of the input data (first step of the Monte-Carlo algorithm), the generation of the Python scripts (used to launch the Abaqus/Explicit code), the extraction of the simulated responses (helping with an external program written in Fortran), the displaying of intermediates results during the process.

3 Experimental set-up

The experimental device used for material behavior identification is a gas-gun, with a caliber of 20 mm and a length of barrel of 1400 mm. The projectiles can be launched 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 and the velocity of the projectiles it's measured just before impact by an opto-electronic system. Initially designed for the Taylor test, this gas-gun can be used successfully for high-speed friction law identification through the experimental test presented in this paper.

For the identification of the friction law parameters associated with a couple of materials, this test consists in launching a projectile into a cylindrical bore as shown in Figure 1. A chamfered part at the head of the projectile facilitates the self-adaptation during the first stage of impact. After impact, one measures the distance between the head of the projectile and the back-face of the target (the extrusion length), which will be the response for the identification procedure.

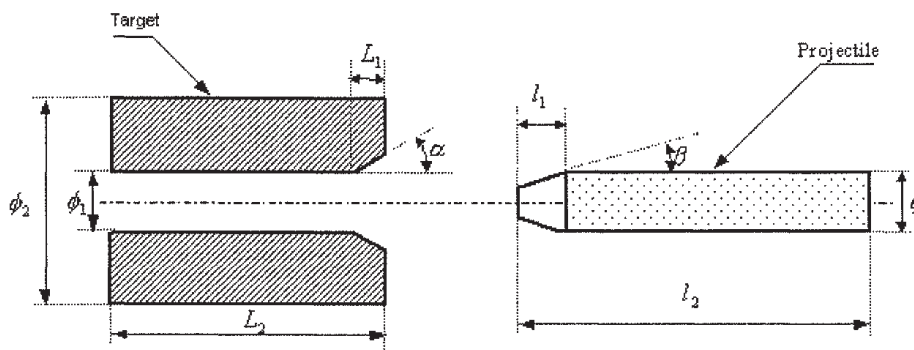


Figure 1: The geometry of the specimens

The experimental work presented in this paper was done in order to identify the friction law parameters for a pair of metallic materials: 42CrMo4 steel for target and 2017 aluminum alloy for projectile. The constitutive flow law parameters of the Johnson-Cook model, for both these materials, under large strain and large strain rate conditions, was determined previously [5] in the same laboratory.

Several tests were achieved for this pair of materials and 5 of them were retained in order to identify and validate the friction law parameter (Table 1).

The test design aims at obtaining the largest part of energy dissipated by friction as possible (at least 60% of total dissipated energy). According to materials, it's a question of optimizing the ratio of extrusion (ratio between projectile diameter and bore diameter), the length of the target, the angles of conical part and the chamfered lengths. The preliminary study of the test leads to the determination, for involved materials, of the following optimized parameters: $L_1 = 10$

mm; $L_2 = 50$ mm; $l_1 = 50$ mm; $l_2 = 10$ mm; $\phi_1 = 9.6$ mm; $\phi_2 = 40$ mm; $\phi = 10$ mm, $\alpha = \beta = 5^\circ$ (Figure1). This design enables on one hand to maximize the energy dissipated by friction during the test and on the other hand to obtain a stopping of the projectile in the target. Thus the extrusion length of the projectile which constitutes the experimental response used by the identification procedure could be measured.

4 Numerical test model

Numerical simulations were conducted using Abaqus/Explicit [1]. The test model is a axially-symmetric as shown in Figure 2 where both initial state and the final state are presented.

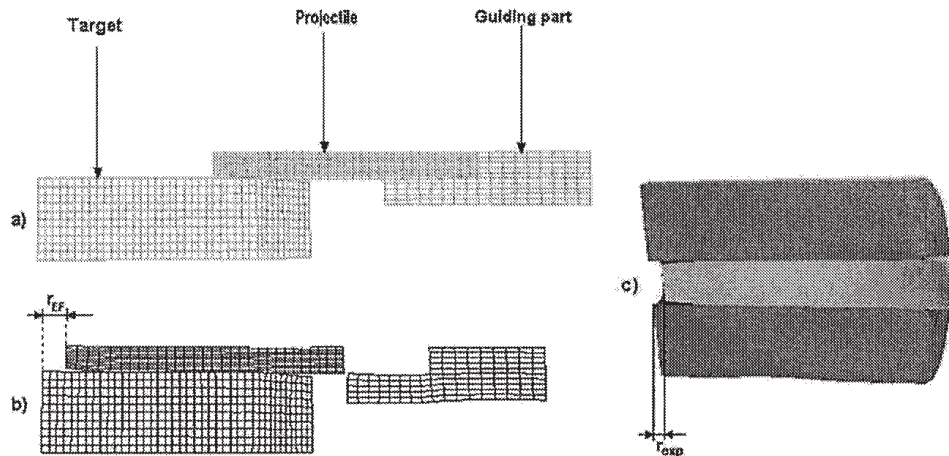


Figure 2: a) Initial state of the FEM; b) Final state of the FEM; c) Post-mortem picture of the specimens

The Coulomb's friction law was introduced here for the contact between projectile and target during the extrusion. This one serves as a test-bed in order to identify the value of the parameter μ of this law, suitable for high slip rates. Starting with this value, the next step will be the identification of parameters for a more complex law, which could take into account the slip rate variation during extrusion.

5 Results and conclusion

The identification of μ was achieved using a single test and the others were used for its validation. For identification was chosen the 4-th test which corresponds to an impact speed of 214.6 m/s. The projectile's speeds of all tests are presented in Table 1.

After experimental test the assembly of target-projectile specimens are measured in order to get the experimental response, i.e. the extrusion length as is figured on the third part of the Figure 2, where one can see a picture of half-assembly after his cutting-out for analysis.

Applying the identification procedure, using the extrusion at 214.6 m/s, there was obtained a friction parameter $\mu = 0.19$ for which the objective function value is 0.01 corresponding to a simulated response of 2.85 mm instead of 2.82 mm. The validation of this parameter using the other tests give quite good results as presented in Table 1. One can observe that as the speed

Test number	Velocity [m/s]	Experimental response [mm]	Simulated response [mm]	Objective function value
1	149.5	11.05	12.50	0.13
2	173.1	9.75	10.53	0.08
3	206.9	2.50	2.68	0.07
4	214.6	2.82	2.85	0.01
5	235.7	-4.96	-4.59	0.07

Table 1: Results of the identification and validation of the friction law

differences between identification test and validation one grow-up, the values of the objective function are increasing, in other words we have a worse validation.

Analyzing the differences between experimental response and simulated one for each test it's easy to observe that a good agreement between these two sets of results could be obtained for a variation of μ , so its value must decrease as the speed values of the extrusion increase. This conclusion leads to the necessary implementation of a new friction law, which must take into account the slip rate variation, as we mentioned before.

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