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THERMO-MECHANICAL MODELLING OF DYNAMIC TENSILE EXTRUSION TEST

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Abstract. Recently, the researchers of the Los Alamos National Laboratory (LANL) have been developed a technique to investigate high strain-rates in which a sphere is launched at high speed (300-800 m/s) through a conical die (Dynamic Tensile Extrusion test).

The system can use a set-up similar to a Taylor test (like a light gusgun) but induces in the material high levels of tensile stresses and allows to investigate the fracture and damage of the material in these extreme conditions. Due to the high strain-rates and hydrostatic component of stress that occur during the extrusion in the die, the material is also subject to a rapid heating.

In this work, the DTE test has been simulated with the explicit Lagrangian code LS-DYNA. In order to correctly reproduce the various aspects of the test it is necessary to use an elasto-plastic material model that takes into account strain-rate, thermal softening, pressure influence and damage and that adequately describes the thermal coupling effects and the equation of state (EOS) of the material. Besides, due to the high distortion of the Lagrangian mesh, the use of a mesh adapting technique is absolutely necessary.

1 INTRODUCTION

A lot of different experimental techniques can be applied to identify material mechanical properties in function of loading conditions, stress/strain distribution, pressure influence, thermal contribution, wave or shockwave propagation and, finally, temperature and strain-rate ranges. In general, it is not possible to completely characterize a material with a single experimental test because each test is limited in strain-rate. At low strain-rate (from 10^{-5} s^{-1} to 10^{-1} s^{-1}) the material transformation is considered to be isotherm without any propagation and dynamic phenomena. The experimental test can be conducted on a standard electro-mechanical or servo-hydraulic machine. In the medium strain-rate test (from 10^{-1} s^{-1} to 10^{2} s^{-1}) the deformation process is still isotherm but the dynamic component of the response starts to be relevant. In this case the tests are performed via pneumatic machine and drop fall. Finally, in the experimental characterization under high value of strain-rate (from 10^{2} s^{-1}) the wave propagation (elastic, plastic or shock waves) is very important and the phenomenon evolution is adiabatic. This implies the overheating of the specimen due to the heat conversion of a

percentage of the mechanical work since the phenomenon duration does not allow the conduction or convection heat dispersion. The experimental test to perform in these conditions are, for example, compression and tensile test on Split Hopkinson Bar, the Taylor test, the flyer impact test and the Dynamic Tensile Extrusion (DTE).

In this work the attention is focused on the material characterization under high value of strain-rate and plastic strain. These input conditions are get via a Dynamic Tensile Extrusion: the experimental concept was developed by Gray III et al. at the Los Alamos National Laboratory [1]. The main objective is the development of a suitable numerical method able to reproduce all the features of the experimental test: quite relevant pressure dependence, strain and strain-rate hardening and coupled thermal softening. Obviously, the choice of the material models used for the mechanical behaviour description is correlated to the goodness of the model to be able to describe these fundamental aspects. In this work the completely empirical Johnson-Cook model, the semi-empirical Steinberg-Guinan and Zerilli-Armstrong models and the phenomenological Mechanical Threshold Stress model are taken into account for what concerns the deviatoric behaviour in addition to a Mie-Grüneisen equation of state for the description of the hydrodynamic behaviour. The numerical simulations are performed with the FEM code LS-DYNA [2], which includes implicit and explicit solver with coupled thermo-mechanical and high non-linear capabilities. The numerical analysis is performed on copper spherical projectile and the numerical results are compared with the experimental results obtained in [1,3,4] and the numerical results obtained via the FEM code MARC in [5].

2 EXPERIMENTAL TEST DESCRIPTION

The Dynamic Tensile Extrusion (DTE) concept was proposed by Gray III et al. in [1]. The test is suitable to evaluate the material mechanical response in case of high plastic strain and strain-rate. These conditions are obtained via a gas-gun facilities without the use of a high-explosive launch system. The experimental results used for the numerical model validation are obtained in [1,3,4].

In case of copper, a spherical projectile (diameter 7.60 mm) is accelerated in a high-pressure helium gas gun at ~400 m/s and extruded through a high-strength steel die (entrance diameter of 7.62 mm, exit diameter of 2.28 mm and angle of 10°). In case of tantalum a spherical projectile (diameter 7.58 mm) is accelerated in a high-pressure helium gas gun at 384 and 553 m/s and extruded through a high-strength steel die (entrance diameter of 7.62 mm, exit diameter of 2.8 mm and angle of 9°).

For both materials the sequence of the segments exiting the die are captured via a high-speed photography [1,3,4] and the results for tantalum are shown in Fig.1 within the reassembly of the recovered segments in sequence of exit. Comparing the results for tantalum specimens at different launch speed it is evident higher velocity implies high elongation and propensity to plastic instabilities of the extruded material. Both in case of copper and tantalum, the material appears to be not fully extruded since the rear portion of the specimen halts in the die.

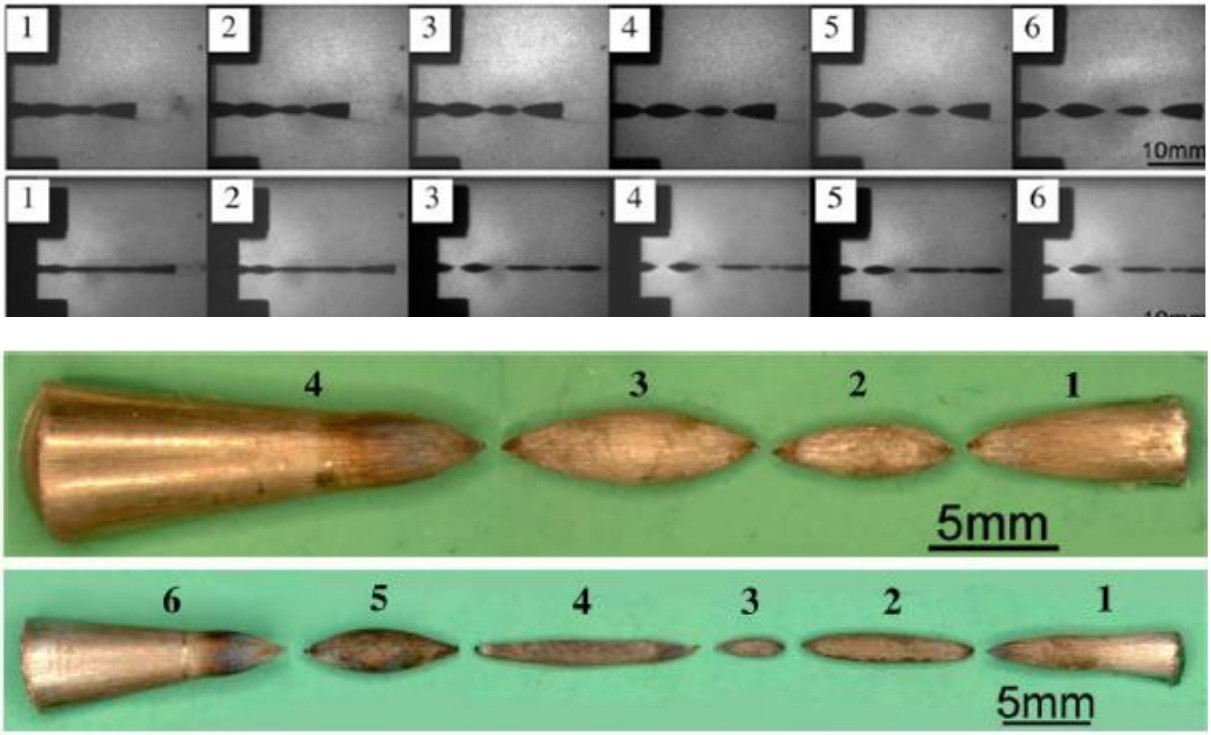


Figure 1: high speed images of the DTE on tantalum launched at 384 m/s and 553 m/s; topology of the recovered extruded Ta sphere launched at 384 m/s and 553 m/s [1,4]

3 NUMERICAL MODEL

The numerical simulations are carried out via the FEM code LS-DYNA [2]. The model is a 2D axis-symmetric model and the solution is obtained by an explicit solver. In order to avoid too high distortion of the Lagrangian mesh, the use of a mesh adapting technique is absolutely necessary (Figure 2).

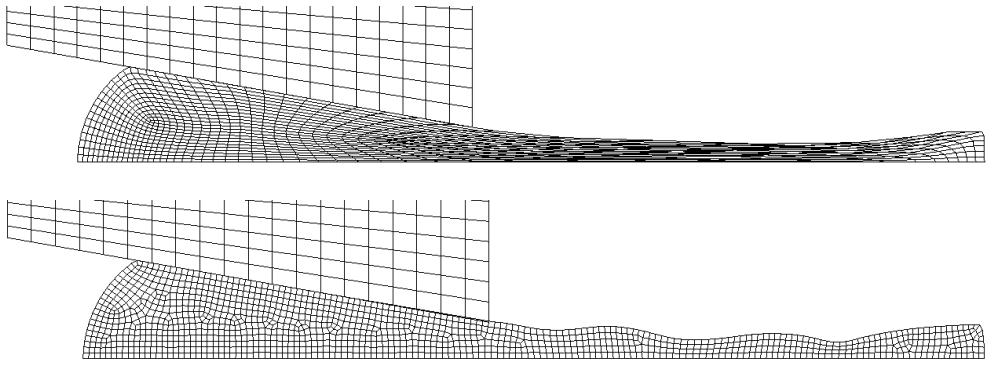


Figure 2: effects of mesh adaptivity on a simulation of DTE: without an adaptive algorithm the mesh is heavy distorted due to the high level of plastic strain reached; with an adaptive algorithm, which remeshes the model at constant time interval, the elements maintain a regular shape and a fixed characteristic dimension

In such kind of problems the choice of the material model (strength model and equation of state) is of fundamental importance: the numerical model has to be able to take into account all the mechanical variables that play a key role in the material deformation process and in the resultant stress and velocity fields. The variable of interest are strain, strain-rate, temperature and pressure.

The phenomenon is strongly thermo-structural coupled (Figure 3): the structural-mechanics material conditions produce the rise in temperature that consequently modifies the mechanical material response. Usually, due to the rise in temperature, there is a decrease of the mechanical strength but also a modification (reduction) in the effect of the strain-rate on the flow stress.

As a matter of fact, the material properties may depend strongly upon the local temperature and for these problems it becomes necessary to compute the temperature throughout the material as time increases. In particular, thermal softening phenomena are essentially due to heat conversion of mechanical work occurring at high strain-rate where strain is localized.

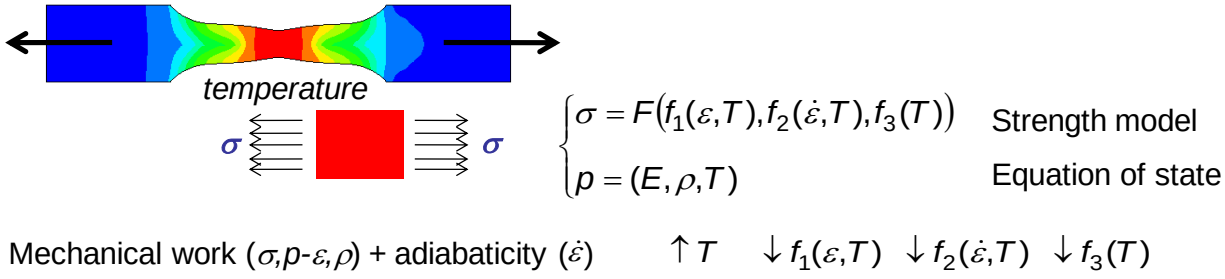


Figure 3: scheme of the thermo-structural coupling

In general, starting from $\dot{\varepsilon} \geq 10^2\ \mathrm{s}^{-1}$ thermal diffusion (conduction and convection) 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 fields, the material temperature could be analytically computed as a function of plastic work

$$T = T_r + \frac{\beta}{\rho \cdot C_p} \cdot \int_0^{\varepsilon_p} \sigma(\varepsilon, \dot{\varepsilon}, T) \cdot d\varepsilon \tag{1}$$

where ρ is the material density, C_p is the specific heat at constant pressure and β is the Taylor-Quinney coefficient [6,7] that represents the portion of plastic work that is converted into heat (for metals about 0.9). The temperature increase is not uniform but grows up in the material with a distribution corresponding to plastic work.

In a more general manner, assuming that the stress tensor and internal energy are state functions of the strain and the temperature, it is possible to evaluate the temperature increment in the material once the strength model and the equation of state of the material are known.

3.1 Strength material model

In past decades a lot of material models for the description of the deviatoric behaviour are proposed. The classification model makes a distinction between empirical, semi-empirical and

phenomenological models. The empirical models have not physical basis, but are obtained by interpolation of the experimental data. On the other hand the phenomenological models are obtained starting from the transformation in the material occurring during a deformation process.

Table 1: Visco-plastic material models

Johnson-Cook [8]	$\sigma_y = \left(A + B\varepsilon_{\mathrm{pl}}^{n}\right)\left(1 + C\ln\dfrac{\dot{\varepsilon}_{\mathrm{pl}}}{\dot{\varepsilon}_0}\right)\left(1 - \left(\dfrac{T - T_r}{T_m - T_r}\right)^{m}\right)$	empirical multiplicative model: temperature T does not influence strain and strain-rate effects (athermal model); no pressure and density influences; melting temperature and shear modulus constant
Zerilli-Armstrong [9]	$\sigma_y = \Delta\sigma_G + B_1\sqrt{\varepsilon_{pl}}\,\mathrm{e}^{\left(-\beta_0+\beta_1\ln(\dot{\varepsilon})\right)T} + \dfrac{k_e}{\sqrt{l}}$ (FCC) $\sigma_y = \Delta\sigma_G + B_0\mathrm{e}^{\left(-\beta_0+\beta_1\ln(\dot{\varepsilon})\right)T} + K_0\varepsilon_{pl}^{n} + \dfrac{k_e}{\sqrt{l}}$ (BCC)	dislocation-based semi-empirical model: athermal and thermal stress components; no pressure and density influences; melting temperature and shear modulus constant
Steinberg-Guinan [10]	$\sigma_y = \sigma_A\, G/G_0$ $G/G_0 = \left[1 + h_1 P v^{1/3} - h_2\left(T - 300\right)\right]$ $\sigma_A = \sigma_0\left[1 + \beta\left(\varepsilon_{pl,i} + \varepsilon_{pl}\right)\right]^{n} < \sigma_{\mathrm{MAX}}$ $T_m = T_{m0}\exp\left[2a\left(1 - v\right)\right]v^{-2\left(\gamma_0 - a - 1/3\right)}$	semi-empirical rate independent model (athermal model); shear modulus function of pressure, density and temperature; melting temperature function of density
Mechanical Threshold Stress [12,14]	$\sigma_y = \hat{\sigma}_A + Gs\hat{\sigma}_T$ $s = \left\{1 - \left[\dfrac{kT\ln\left(\dot{\varepsilon}_0/\dot{\varepsilon}\right)}{g_0 Gb^3}\right]^{1/q}\right\}^{1/p}$ $\theta = \left(a_0 + a_1\ln\left(\dot{\varepsilon}\right) + a_2\dot{\varepsilon}\right)\left[1 - \dfrac{\tanh\left(\alpha\hat{\sigma}_T/\hat{\sigma}_S\right)}{\tanh(\alpha)}\right]$ $\hat{\sigma}_S = \hat{\sigma}_{S0}\left(\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_{S0}}\right)^{\frac{Gb^3A}{kT}}$ $G = G_0 - \dfrac{G_T}{\mathrm{e}^{t/T} - 1}$	dislocation mechanism based model (mechanical threshold stress as internal state variable): athermal and thermal (thermal activation and controlled drag) stress components; no pressure and density influences; shear modulus function of temperature

Models such that proposed by Johnson-Cook (J-C) [8] is purely empirical model and it is one of the most widely used. An example of semi-empirical model is the Zerilli-Armstrong

(Z-A) model [9], that is obtained on the basis of the dislocation mechanics theory and presents a different formulation for BCC and FCC materials. Another example of semi-empirical model is the Steinberg-Cochran-Guinan-Lund (S-C-G-L) model [10,11], which was first developed for the description of high strain-rates behaviour [10], and after extended to low strain-rates [11]. A phenomenological more complex dislocation-based model is the Mechanical Threshold Stress (MTS) model [12].

In general, a visco-plasticity model express the flow stress as a combination of athermal and thermal components. The athermal part of the stress can be in general correlated with strain, strain-rate, temperature and pressure, while the thermal component identifies the temperature influence on the strain-rate effects on the flow stress (temperature-strain-rate coupling).

The J-C model [8] is the most simple model able to predict the mechanical behaviour of the materials under different loading conditions. Besides, as mentioned before, it is one of the most used material model, so it is implemented in many FEM codes and it is quite easy to find in literature the values of J-C parameters for different materials. In the J-C model only the athermal stress component is taken into account and it expresses the flow stress as reported in Table 1. In more details, A is the elastic limit strength, B and n are the work hardening parameters. C and $\dot{\varepsilon}_0$ express the strain-rate sensitivity coefficients and m describe the thermal softening. In more details, $\dot{\varepsilon}_0$ represents the quasi-static strain-rate threshold, that, ideally, represents the highest strain-rate for which the strain-rate effects on the flow stress are negligible. Finally, the thermal effects are described, in function of the temperature T, the reference temperature at which there are not any thermal effects T_r and the melting temperature at which the material mechanical strength goes to zero T_m. In this condition the material loses its shear strength and starts to behave like a fluid. The J-C model is a multiplicative model, in which the effects of plastic strain, strain-rate and temperature are assumed to act independently. The J-C model is quite inaccurate to model the material behaviour in case of high pressure conditions. As a matter of fact, it neglects the influence of the pressure and changes in volume on the flow stress. Besides, it considers the melting temperature as a constant, while the solid-liquid transition is influenced by the density.

The Z-A [9] model is based on simplified dislocation mechanics, and as the J-C model, it neglects the pressure and densities influences and considers the shear modulus and the melting temperature to be constants. At difference from J-C model it takes into account also the thermal component of the stress. Since it is partially physical-based, it presents a different flow stress formulation for FCC and BCC materials. In reference to the Table 1, in the Z-A models, l represents the polycrystal grain diameter and $\Delta\sigma_g$, B_0, B_1, β_0, β_1, K_0, n and k_e are experimental constants based on a dislocation mechanics analysis of the plastic deformation mechanism operative in the two different crystal lattice structures.

A more accurate model is the S-G material model [10] in which both the flow stress and the shear modulus are function of temperature, strain and also pressure. In reference to Table 1, v is the relative volume, β and n are the work-hardening parameters and $\varepsilon_{pl,i}$ is the initial equivalent plastic strain, normally equal to zero. The subscript 0 refers to the condition in which T=300 K, P=0 and ε=0, the reference state. h_1 and h_2 are proportional to the derivative of the yield stress respect to the pressure and the derivative of the shear modulus respect to the temperature, respectively. Also for this model, if the temperature overcomes the melting

temperature then the material strength goes to zero, but in this case the melting temperature is not constant but is a density function. The S-G model is strain-rate independent (athermal stress component), according to the fact that for strain-rates greater than ~10^5 s^{-1} the rapid decrease of rate dependent effects with increasing dynamic stress may be explained by the increase in temperature with increasing stress [10]. This assumption is reasonable in case of FCC material, like copper, but it is quite inaccurate in case of BCC materials [11].

The last material model takes into account in this work is the MTS model [12] which is quite different from the previous ones because it uses the mechanical threshold stress as the internal state variable (instead of the strain) and treats evolution of this variable using physically based and phenomenological based expression. In reference to Table 1, the flow stress is separated into two components: the athermal component $\hat{\sigma}_A$ characterizes the rate independent interactions of dislocations with long-range barriers such as grain boundaries, while the thermal component $\hat{\sigma}_T$ characterizes the rate dependent interaction with short range obstacles. The factor *s* is related only to the thermally activated controlled glide in according to the results of [13] that indicates at strain-rate lower than ~10^4 s^{-1} the rate controlling deformation mechanism is thermal activation while the contribution of dislocation drag is negligible. *s* is evaluated via an Arrhenius rate equation, where $\dot{\varepsilon}_0$ is a constant, *k* is the Boltzmann constant, g_0 is the normalized activation energy, *G* is the shear modulus, *b* is the magnitude of the Burger's vector and *p* and *q* are constants that characterize the shape of the obstacle profile. In the definition of the strain hardening rate θ, the first terms is the hardening due to dislocation accumulation (a_0, a_1 and a_2 are material constants) and the second one is the dynamic recovery rate, that is related to the threshold stress at zero-hardening $\hat{\sigma}_S$, correlated to the saturation threshold stress for deformation at 0 K $\hat{\sigma}_{S0}$ ($\dot{\varepsilon}_{S0}$, and *A* are constants). Finally, the shear modulus *G* temperature dependence is expressed according to the results found in [14].

In addition in LS-DYNA [2] it is possible to combine each material strength model with an element failure model. In particular, it is possible to define one (or more) condition for the deletion (erosion) of the elements: when the condition is reached the element is cancelled from the model. In case of the DTE simulations the condition is imposed on the value of the maximum effective strain.

Similarly, the standard LS-DYNA J-C model provides also a failure model for which the strain at fracture is given by

$$\varepsilon_f = \left(D_1 + D_2 \mathrm{e}^{D_3 \sigma^*} \right) \left(1 + D_4 \ln \dot{\varepsilon}^* \right) \left(1 + D_5 T^* \right) \tag{2}$$

where D_1, D_2, D_3, D_4 and D_5 are the failure parameters and σ^* is the ratio between the pressure and the effective stress. The material fracture occurs when the damage parameter

$$D = \sum \frac{\Delta \varepsilon_p}{\varepsilon_f} \tag{3}$$

reaches the value of 1.

3.2 Equation of state

The other fundamental aspect to consider is the implementation of an equation of state to simulate the hydrodynamic material behaviour. An EOS is a constitutive relation between state variables and describes the state of the matter. Usually it expresses a thermodynamic variable (such as pressure) in function of two other independent state variables (such as density and internal energy).
In general the equations of state can be divided into two categories: analytical EOS and tabular EOS.

In LS-DYNA [2] the equations of state for metals are in general partitioned into two terms: a cold pressure and a thermal pressure (see equation 4). The first terms $P_C(\mu)$ is a function of the density and is hypothetically evaluated along a 0 K isotherm, while the second one $P_T(\mu,E)$ depends on both the density and the internal energy per unit volume of the system

$$P(\mu, E) = P_C(\mu) + P_T(\mu, E) \tag{5}$$

where $\mu=\rho/\rho_0-1$. It is clear that for a compressed material $\mu>0$, for an expanded material $\mu<0$ and if no load is applied to the material $\mu=0$. More precisely the EOS implemented have the general form

$$P(\mu, E) = A(\mu) + B(\mu)E \tag{6}$$

so the pressure is a general function of the density but linearly depending by the energy per unit volume.

The analytical equation of state implemented in LS-DYNA and used in this work is the Mie-Grüneisen EOS, that is able to describe the behaviour of a solid material. It defines the pressure for compressed materials as

$$P = \frac{\rho_0 C_0^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2}\right)\mu - \frac{a}{2}\mu^2\right]}{\left[1 - (S_1 - 1)\mu - S_2 \frac{\mu^2}{1+\mu} - S_3 \frac{\mu^3}{(1+\mu)^2}\right]^2} + (\gamma_0 + a\mu)E \tag{7}$$

and for expanded materials as

$$P = \rho_0 C_0^2 \mu + (\gamma_0 + a\mu)E \tag{8}$$

where ρ_0 is the initial density, C_0 the sound speed, γ_0 the Grüneisen parameter that defines the effect on the atoms vibration consequent to the change in energy (or temperature), S_i are the coefficients of the polynomial that defines the shock wave velocity as function of particle velocity and a is the first volume correction to γ_0.

4 NUMERICAL RESULTS AND DISCUSSION

A great number of simulation are performed in order to investigate the effects of the various numerical model aspects on the results of a DTE on copper specimen.

This type of test is used as a benchmark of numerical model capabilities to reproduce a phenomenon in extreme conditions of strain, strain-rate, temperature and pressure. In this preliminary phase, the interest is focused on the understanding of the more important model

parameters and modelling choices to correctly reproduce the real behaviour. In the future, when experimental data of this kind of test will be available, it will be possible to use a combined experimental and numerical approach to obtain the strength model parameters of material under investigation. For this reason, the value of the material model parameters used in these simulations are those reported in the original works of the model authors [8-12].

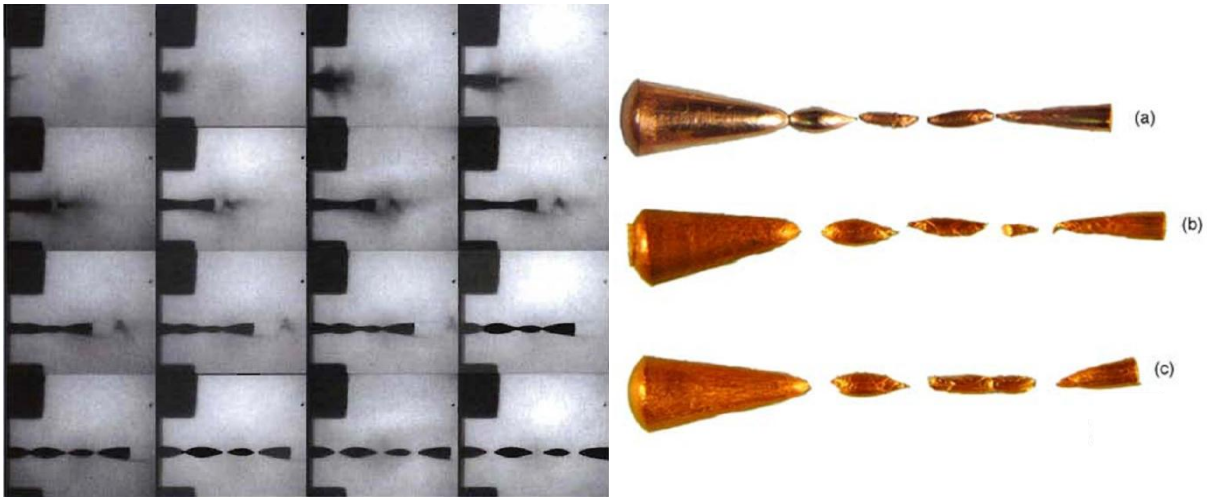


Figure 4: high-speed imaging showing the deformation of an extruded Copper sphere which entered the die at 400 m/s (time intervals 4 μs) [3]; dynamic tensile extrusion of Copper for (a) 65 μm, (b) 118 μm and (c) 185 μm grain size [1]

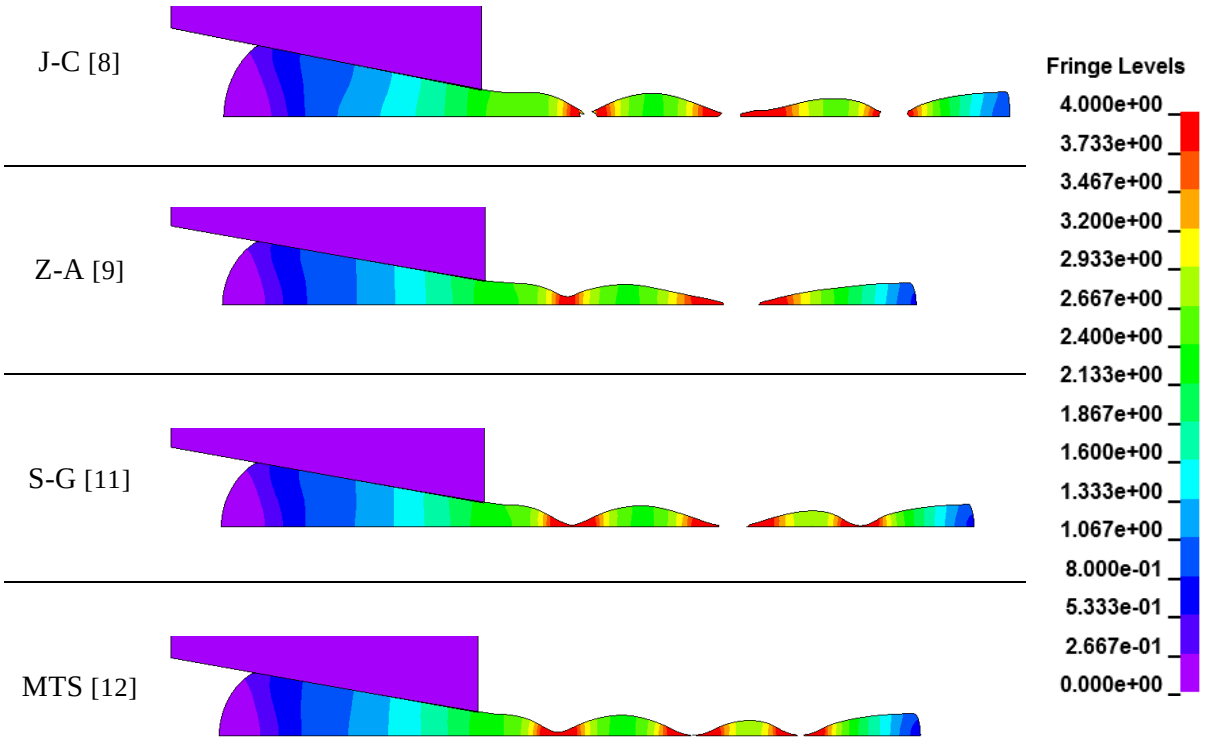
Figure 4 shows some results presented in [1,3] in terms of shape evolution during the test and final geometry of the recovered samples (no other experimental measurement is available).

Table 2 summarizes the set of numerical results in terms of plastic strain for the copper sphere (diameter 7.60 mm) launched at 400 m/s. The die (entrance diameter of 7.62 mm, exit diameter of 2.28 mm and angle of 10°) is modelled as a rigid body (E=200 GPa) and the contact with the specimen is frictionless. The results are shown at the same time step (48 μs after the impact).

For all the material models, the deformed shape has a good likelihood with the experimental test results even if the model parameters are not optimized. The level of plastic strain is comparable for all the models, as showed in Table 2, but the speed of the projected pieces is different due to a different flow stress evaluation that implies a different energy dissipation (plastic work).

As mentioned before, these results are obtained with the data available in [8-12]; with a change of some material parameters the results of the numerical simulations becomes much more similar to the experimental ones. In an empirical model (such J-C) all the parameters affect the results and could be changed to obtain a best fit, but this may be very complicate without results from other type of tests or a suitable optimization strategy. On the other hand, with a phenomenological model the number of parameters that is sensible to change is usually limited.

Table 2: numerical results in terms of plastic strain for the simulation of the DTE test on copper sphere launched at 400 m/s: comparison between different material models



To understand the typical distribution of mechanical and thermo-dynamical quantities in such problems, in Table 3 the results for S-G material model at two different time are reported. At 21 μs after the impact, the sample is still in the die, subjected to high compression stress, strain and strain-rate with an increase in the particle velocity from the initial 400 m/s up to about 1 km/s. The pressure level is in the order of 2 GPa, and the temperature increment is about 200 K.

When the material is extruded outward, the stress, strain and strain-rate become positive (tension) and due to the high velocity and plastic instability, the strain level grows up and the deformation is localized. In this phase the pressure falls down but the temperature grows up in the heavy deformed portions, with an increment of about 500 K.

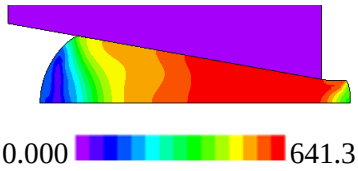
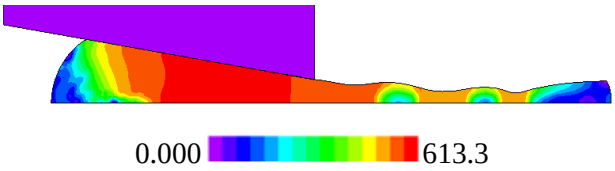
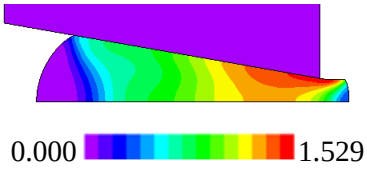
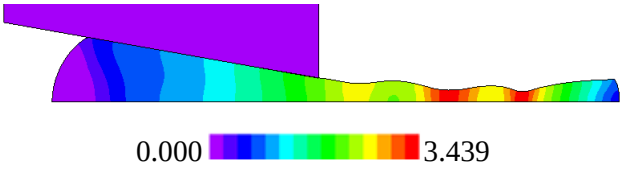
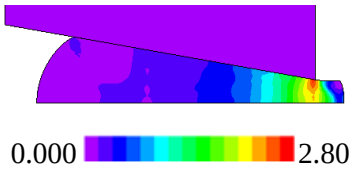
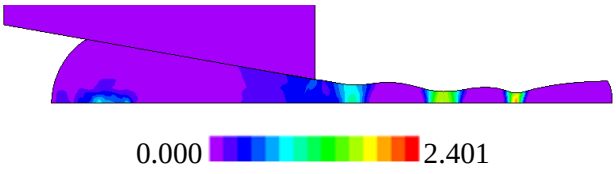
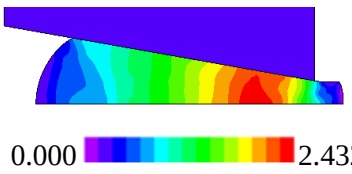
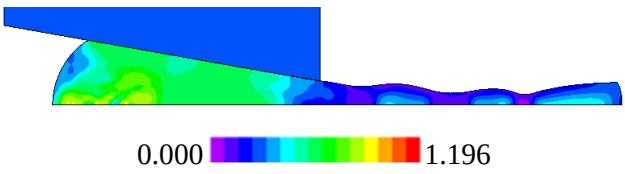
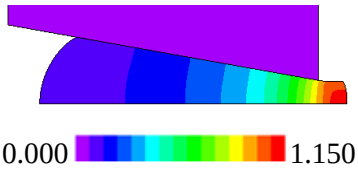
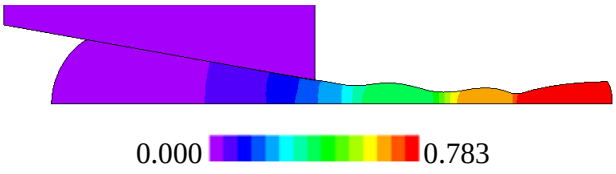
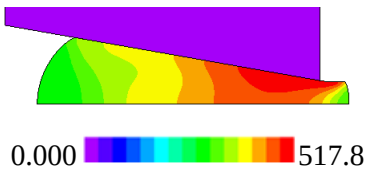
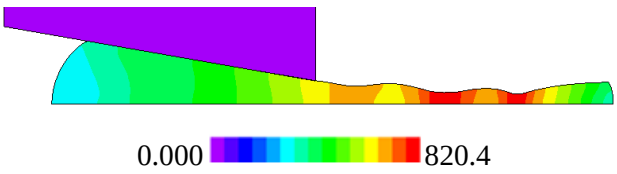
CONCLUSION

Recently, the researchers of the Los Alamos National Laboratory (LANL) developed a technique to investigate high strain-rates in which a sphere is launched at high speed (300-800 m/s) through a conical die (Dynamic Tensile Extrusion test).

The system can use a set-up similar to a Taylor test (like a light gusgun) but induces in the material high levels of tensile stresses and allows to investigate the fracture and damage of the material in these extreme conditions. Due to the high strain-rates and hydrostatic component

of stress that occur during the extrusion in the die, the material is also subject to a rapid heating.

Table 3: numerical results for the simulation of the DTE test on copper sphere launched at 400 m/s: S-G strength material model

Quantity	**21 μs**	**36 μs**
VM (MPa)		
ε_{pl} (-)		
SR (10^5 s^{-1})		
P (GPa)		
v (km/s)		
T (K)		

In this work, the DTE test was simulated with the explicit Lagrangian code LS-DYNA. In order to correctly reproduce the various aspects of the test it is necessary to use an elasto-plastic material model that takes into account strain-rate, thermal softening, pressure influence

and damage and that adequately describes the thermal coupling effects and the equation of state (EOS) of the material.

Several strength material models both empirical and phenomenological were compared.

Besides, due to the high distortion of the Lagrangian mesh, the use of a mesh adapting technique was absolutely necessary.

The simulations were compared with available experimental results from tests performed on pure copper, at Los Alamos National Laboratory.

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