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Numerical simulations of Taylor anvil-on-rod impact tests using classical and new approaches

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Abstract

Plastic deformation of samples undergoing Taylor anvil-on-rod impact test is simulated utilising finite element method (FEM). Classical (bilinear plasticity using von Mises stress, Johnson-Cook plasticity model) plasticity models and a new plasticity model based on notion of incubation time of plastic flow initiation are employed to model dynamic deformation of tested samples. In order to verify the obtained solutions, the received predictions are compared to available experimental measurements of deformed sample shapes for two different materials (copper, aluminium) and various initial sample velocities. It is shown that bilinear von Mises plasticity model is not able to provide satisfactory coincidence between the shape of the sample boundary received in numerical simulations and in real experimental conditions. At the same time, models accounting for rate dependency of deformation are providing much more accurate results. Substitution of the concept of "dynamic" yielding stress of a material, depending on the rate of deformation by characteristic time of plastic stress relaxation provides a powerful tool for robust prediction of plastic deformation for a wide range of strain rates. The parameter of the characteristic relaxation time has a clear physical interpretation and theoretically can be evaluated from microstructural studies.

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Keywords: Taylor test; FEM; incubation time; copper; aluminium;

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1. Introduction

Taylor anvil-on-rod impact test Taylor (1948), Whiffin (1948) Carrington, Gayler (1948) is one of the most convenient and simple ways to evaluate dynamic characteristics of a material deformation. High-rate stresses are developed at the end of the rod colliding with an anvil. Should these stresses exceed the corresponding dynamic yield strength of the material, the plastic wave appears and propagates along the cylinder causing permanent plastic change of the sample geometry. In that part of the rod where the stresses do not exceed the definite limit, deformations remain purely elastic Wilkins, Guinan (1973). Initially, all the experimental analysis was based only on the comparison of initial and final lengths of the rod, providing a possibility to estimate “dynamic yield stress”. Further development of experimental methods made it possible to track deformation of the sample during impact with high time resolution and also record the oscillation profile of the back surface of the rod using laser interferometry Eakins, Thadhani (2006). All this progress converted Taylor's test into an extremely very powerful method of investigation of high-speed processes inside dynamically deformed material. A "mushroom" shape of the rod end is often appearing as the result of deformation for a number of metals and alloys Borodin, Mayer (2015). The shape of the profile of the rod and its change in the process of deformation Eakins, Thadhani (2006), Borodin, Mayer (2015) provides significant information about the mechanisms of plastic deformation (ex. localization of plastic flow, etc.). Should the mechanisms leading to plastic deformation of materials undergoing high-rate loafing be understood, this will open new prospects for development of new materials with desired resistance to dynamic loading.

Nowadays a number of models of plastic deformation and plasticity criteria have been used by various authors to describe Taylor's tests Wilkins, Guinan (1973), Eakins, Thadhani (2006), Mase (1970), Johnson, Cook (1983), Steinberg et al. (1980) but they all have their drawbacks. Many of these models are included in popular commercial FEM codes (ANSYS, LS Dyna, etc.). The classic von Mises criterion Mase (1970) was actively used in the middle of the last century (ex. Wilkins, Guinan (1973)) and is still used by various authors. It is known Krasnikov et al. (2011) that this approach is essentially "quasistatic" and cannot be used for prediction of high-rate deformation as it does not take into account any dynamic effects Borodin et al. (2014). In Johnson-Cook model Johnson, Cook (1983), which is the most widely used model to describe dynamic deformation, additional velocity and temperature dependences are introduced. The same is regards in the models of Steinberg-Guinan Steinberg et al. (1980) and Zerilli-Armstrong Armstrong, Walley, (2008). The appearance of the latter was in many ways inspired by the need to describe the complex shape of the rod obtained in the Taylor tests. At the same time, all these models have very limited range of deformation rates, for which they provide reliable results (usually less than 10^4 s-1) and their parameters are of purely tuneable nature. The behaviour these parameters, in particular, the speed sensitivity of stresses (which changes by almost an order of magnitude with an increase in the strain rate from 10^2 s-1 to 10^4 s-1 Suo et al (2013), Gurrutxaga-Lerma et al. (2015), as well as the appearance of refinements of the models for additional adjustability of speed sensitivity parameters Couque (2014) indicate imperfection of these approaches and the need for their modification.

The change in the concept of the dynamic yield strength was done by introduction of integral plasticity criteria Gruzdkov et. al (2002, 2008, 2009) and associated new parameter of characteristic relaxation time, reflecting the time occupied by plastic deformation process. In the general case, this approach leads to the following form of the integral inequality:

$$I(t) = \int_0^t \sigma(s) K(t-s)\, ds \le \sigma_y^0, \tag{1}$$

where the kernel of the integral operator $K(t)$ is the function controlling the time sensitivity of the deformation process. The criterion (1) for quasi-static times turns into classic quasi-static yield condition $\sigma_y \le \sigma_y^0$.

2. FEM implementation

All the three discussed plasticity models (bilinear von Mises plasticity, Johnson-Cook model, incubation time model) were introduced into ANSYS FEM software. In the numerical modelling of the Taylor test, a 2D problem is solved, using the axial symmetry of the problem. The impact of a half of the sample cross-section on an absolutely rigid obstacle is simulated. Fig. 1 shows typical cross sections before and after impact.

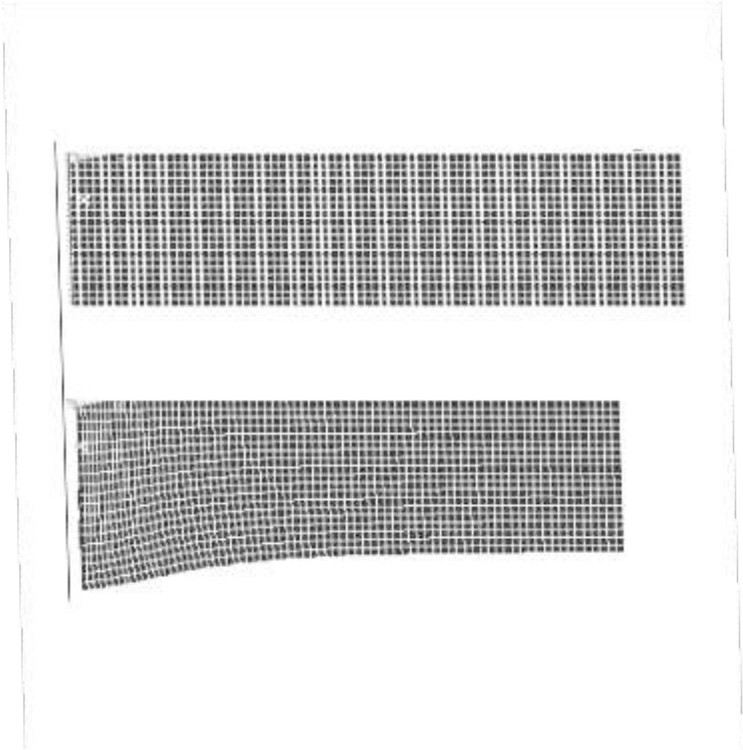

Fig. 1. Typical shape of sample cross section before and after impact.

3. Calculation results

To compare the results of numerical simulation, experimental data was taken from House (1989). In these experiments, Taylor tests were carried out for various alloys and metals.

Table 1. Experimental data House (1989) for the change in the length of aluminium rod for different speeds.

Impact velocity (m/s)	Finial length change (mm)
211	1.58
223	1.86
239	2.26
263	2.64
327	3.79

Table 1 gives the dependence of the length change of aluminium alloy 6061 T6 (quasistatic yield limit - 315 MPa, density – 2710 kg/m3) for different the impact speeds. In these experiments, rods were having initial diameter of 7.595 mm and initial length of 15.19 mm.

For each impact velocity, numerical calculations were made for different values of yielding process incubation time. Fig. 2 gives the dependence of the change in length of the rod for different values of incubation time for initial velocity equal to 327 m/s.

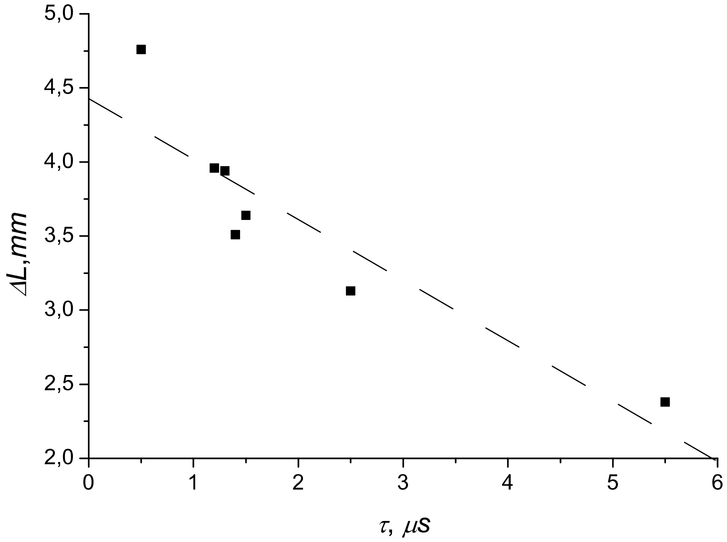

Fig. 2. Change of the rod length as a function of incubation time (impact velocity is 327 m/s).

Same calculations were performed for other available impact velocities (see table 1). The received dependencies for sample shortening are given in figure 3.

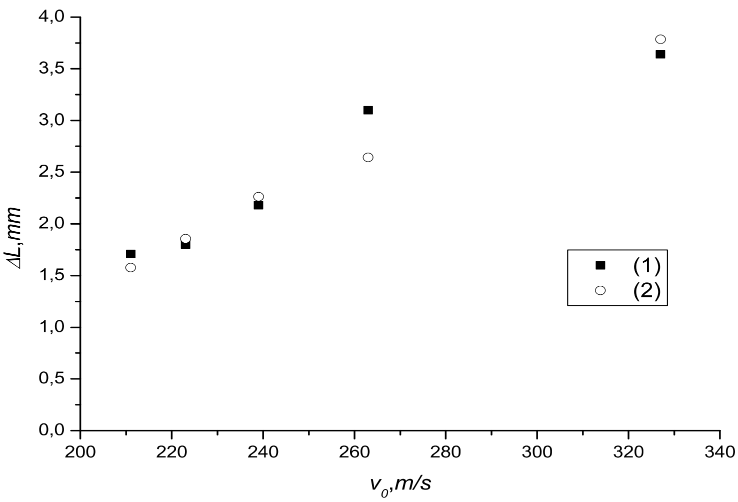

Fig. 3. Sample shortening as a function of initial impact velocity for the value of incubation time equal to 1.5 ms. 1- experimental points House (1989), 2- numerical simulation.

Fig.4 shows the calculated and experimental Eakins, Thadhani (2006) profile of the copper sample rod at the time equal to 58.4 μs after the collision with the anvil. In experiments Eakins, Thadhani (2006), the process of deformation of a copper rod is registered with a high-speed camera, providing a possibility to measure surface profile at every instant of time.

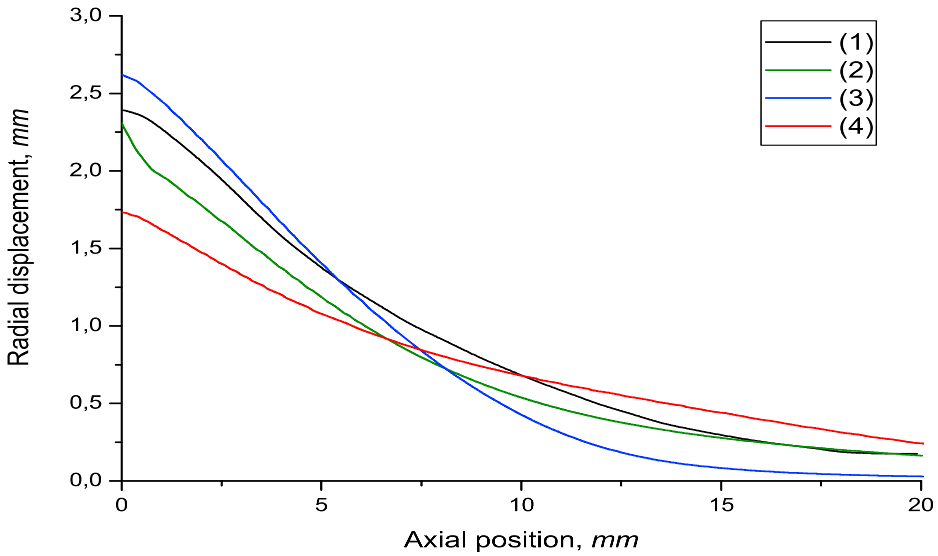

Fig. 4. Experimentally measured [24] – (1), and calculated using von Mises approach - (3), Johnson-Cook approach -(4) and incubation time approach – (2) radial displacement of sample surface for time equal to 58.4 μs and initial velocity equal to 83 m/s.

As evident from figure 4, the von Mises approach in not giving a possibility to correctly predict sample deformation at points distant from the contact surface. Johnson-Cook approach is giving predictions of surface displacements that are far from those observed in experiments. Incubation time based approach is giving a much more accurate estimation of displacements. In is noteworthy that the utilized approach (incubation time approach) is using only one additional material parameter (incubation time of yielding onset).

4. Calculation results

It was shown that application of yielding condition based on the approach using notion of incubation time of yielding onset is making it possible to receive correct predictions of deformation of some metallic materials in conditions of Taylor anvil-on-rod impact test without introduction of complicated strain-rate dependencies and introduction of multiple parameters not having a clear physical meaning. The discussed yielding criterion is utilising only one additional parameter comprising characteristic time of relaxation processes in the plastically deformed material that can be measured experimentally or even evaluated from microstructural studies.

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