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Finite Element Modeling of a Symmetric Taylor Impact Test

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Abstract. Symmetric rod-on-rod Taylor testing is applied for the determination of high strain rate mechanical properties. The deformation of the specimen is highly complex in this testing method. We examined the evolution of the deformation and temperature in a copper specimen by using a coupled thermo-mechanical finite element simulation for three different impact velocities.

Keywords: Taylor impact test, rod-on-rod, Johnson-Cook materials model, finite element method

1 Introduction

Large strain magnitude and strain rate deformation of metallic structural materials can arise at bullet impact, veichle collision or at high speed metal forming, such as explosion forming or electrodynamic forming. During these deformations, the plastic deformation rate can excess > 10^3 s^{-1}. The macro deformation of the materials are determined by the mass effect, strain hardening, strain rate sensitivity, and softening due to the temperature increase arising from the plastic deformation. In the Taylor impact test [1, 2], a cylindrical specimen is impacted to a rigid wall, and by evaulating the deformed geometry, the dynamic stiffness can be estimated. In the modified version of the test, the specimen is impacted with a receiver specimen by the rigid wall. This is called the rod-on-rod (ROR) or symmetric Taylor impact test [3, 4]. For the finite element analysis of the deformations, a material model is selected that can follow the material behavior at the large deformation rates, the Johnson-Cook material model [5].

In this paper, we present a finite element modeling of a rod-on-rod Taylor test on a copper specimen. For the material model, we employed the Johnson-Cook model. The impact was evaluated at three impact velocities, at which plastic deformation arise, but ductile damage is avoided.

2 Modeling

Finite element modeling of the rod-on-rod Taylor test was performed in MSC Marc. The initial diameter of both cylindrical specimens were d_0 = 7.62 mm, the lengths were l_0 = 25,4 mm. Employing axisymmetry, a planar model were generated of half of the specimen sections. The mesh density was increased in the direction of the impacting surface. The wall was considered as rigid, and all contacts were considered as frictionless. The impact velocities (v) were: 130 m s^{-1}, 190 m s^{-1}, and 250 m s^{-1}.

The material of the specimen was modelled as elastic-plastic. The elastic properties were: elastic modulus: 110 GPa, Poisson's ratio: 0.33. The plastic material model was the Johnson-Cook model [5]:

$$k_f = \left(A + B\varepsilon_{eq}^n\right)\left(1 + C \cdot \ln\frac{\dot{\varepsilon}_{eq}}{\dot{\varepsilon}_0}\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right) \quad (1)$$

where k_f is the flow stress, ε_{eq}^n is the equivalent strain, $\dot{\varepsilon}_{eq}$ is the equivalent strain rate, and T is absolute temperature. Material properties of the model for copper were: A = 90 MPa, B = 292 MPa, n = 0.31, C = 0.025, m = 1.09, $\dot{\varepsilon}_0$ = 1 s^{-1}, T_r = 300 K [1]. Flow curves calculated from the model are shown in Fig. 1 for temperatures of 300 K and 600 K, at strain rates of 1 s^{-1} and 10^5 s^{-1}.

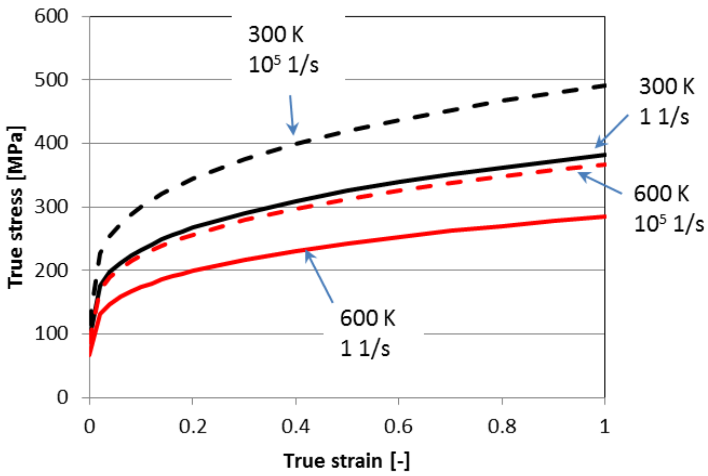

Fig. 1. Flow curves of copper calculated from the Johnson-Cook model.

Further material properties of copper in the simulation: melting point: T_m = 1356 K, density: 8960 kg m^{-3}, specific heat capacity: 383 J kg^{-1} K^{-1}, heat conduction: 401 W m^{-1} K^{-1}, coefficient of thermal expansion: 16.6 ppm K^{-1}.

Simulations were excecuted in the coupled thermo-mechanical case, with a dynamic transient (explicit) solver, using a single step Houbolt procedure, with the large strain option. The time step was set about 10^{-7} s, determined from the eigen frequency analysis, refined at around the second harmonic frequency.

3 Results and conclusions

Deformation of the specimens are shown in Fig. 2 at 250 m s^{-1} impact velocity, 240 μs after the impact. The gray scale shows the equvalent plastic strain. Comparing to the results of the conventional Taylor test [2], the resulting deformation in the rod-on-rod test is smaller at the same impact velocity [4]. In the case shown in Fig. 2, the largest equivalent strain is about 1, while in the conventional test it develops at around 130 m s^{-1} in the specimen, and strains over 2 are reached at an impact velocity of 190 m s^{-1} [2]. Above 190 m s^{-1} impact velocities, ductile damage occurs in the specimen [4] in the conventional Taylor testing, while in the rod-on-rod test, higher velocities can be allowed, the maximum was chosen as 250 s^{-1}. By analysing the deformations in the specimens in Fig. 2, we can conclude, that the deformations in the specimens are not symmetric, the deformations in the receiver are distributed over a larger volume, than in the impactor, nevertheless the maximal strain are of similar magnitudes in both specimens.

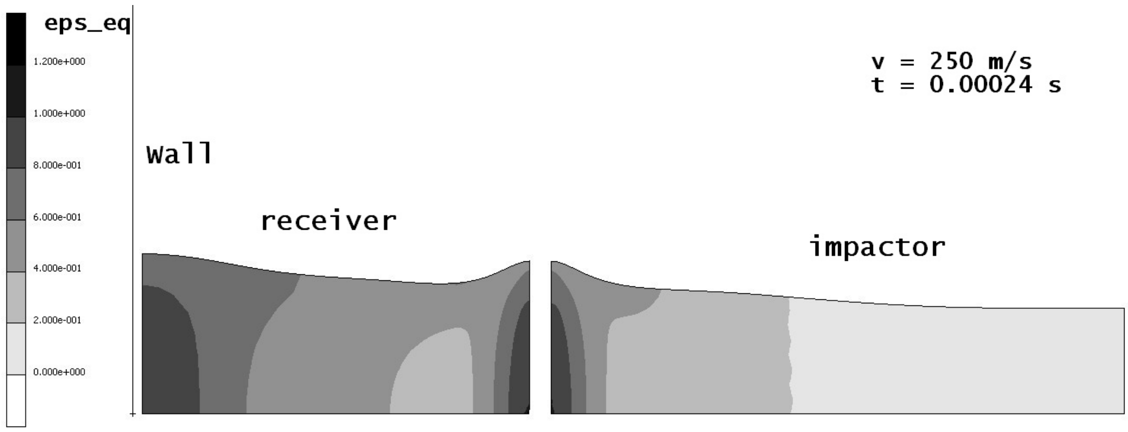

Fig. 2. Deformations of the specimens at 250 m s^{-1} impact velocity, at 240 μs after the impact. Gray scale shows equivalent strain.

The distribution of the deformations along the axis of symmetry of the specimens for different impact velocities are shown in Fig. 3. The maximum eqivalent strains are about 0.3, 0.6 and 1 for 130, 190, and 250 m s^{-1} impact velocities, respectively. Strains at the contact nodes between the specimens (at 0.025 m distance from the wall) increases suddenly and considered as a numerical error in the calculations.

In the thermo-mechanical model, the maximum temperature increase in the specimens are 30, 70 and 130°C for the 130, 190, and 250 m s^{-1} impact velocities, respectively (Fig. 4). The largest temperature arises in the receiver specimen at the contact with the wall; at contact surface between the specimens, the temperature increase is about 5-20 °C lower. In the conventional Taylor test, the calculated temperature rise is significantly larger: about 160, 190, and 340°C for 130, 144 and 190 m s^{-1} impact velocities [2].

Analyzing the temperature distributions, the large temperature increase is located in the 5 mm vicinity of the mutual contact of the specimens; as well as at the 10 mm range vicinity of the contact by the wall in the receiver specimen.

The temperature increase causes softening, therefore smaller resistance against further deformations, nevertheless, significant softening only occures by the largest impact velocity for the rod-on-rod impact test.

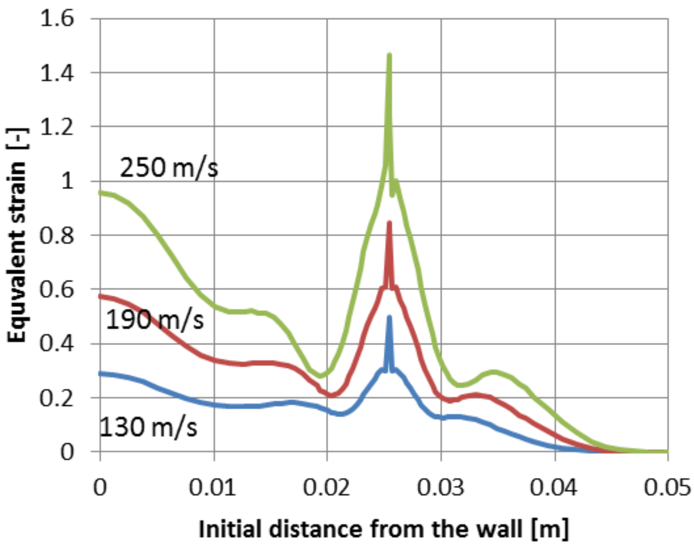

Fig. 3. Equivalent plastic strain on the axis of symmetry as a function of the distance from the wall, at 240 μs after the impact for 130, 190, and 250 m s^{-1} impact velocities. The contact between the specimens is located at 0.025 m.

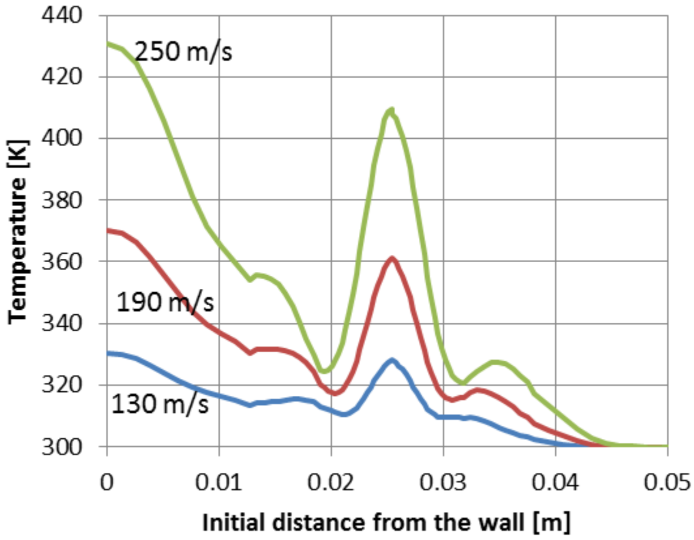

Fig. 4. Temperature distribution on the axis of symmetry as a function of the distance from the wall, at 240 μs after the impact for 130, 190, and 250 m s^{-1} impact velocities. The contact between the specimens is located at 0.025 m.

Three deformation regimes can be distinguished by analysing the strain distribution along the axis of symmetry: there are high deformations on the impactor specimen in the close vicinity of the contacting surface (0-5 mm), then a low plastic deformed zone, followed by an zone where no plastic deformation remains, only elastic. In the receiver specimen, there are large plastic deformations in the vicinity of the contact surfaces, which enclose a medium deformed zone.

The reaction force arising in the wall as a function of time during the impact is shown in Fig. 5 for the different impact velocities. The force slowly increases in the first stage of the impact, then it starts increasing rapidly while the deformation and the hardening of the specimen increases. After reaching the maximum, the force drops rapidly, when the specimens bounce back from the wall. The post-impact velocity of the specimens are about 10% of the impact velocity. The duration of the plastic deformation is about 120-150 μs.

After the impact, when the large compressive stress causing large plastic deformations due to the impact decays, complex elastic vibrations remain in the specimens.

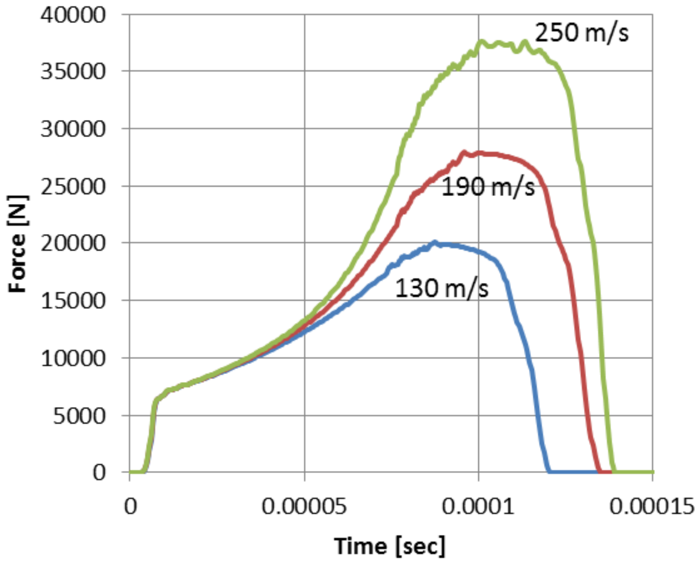

Fig. 5. The reaction force arising in the wall as a function of time for 130, 190, and 250 m s^{-1} impact velocities.

Acknowledgement

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