Validating Material Modelling for OFHC Copper Using Dynamic Tensile Extrusion (DTE) Test at Different Velocity Impact

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Abstract. In the Dynamic Tensile Extrusion (DTE) test, the material is subjected to very large strain, high strain rate and elevated temperature. Numerical simulation, validated comparing with measurements obtained on soft-recovered extruded fragments, can be used to probe material response under such extreme conditions and to assess constitutive models. In this work, the results of a parametric investigation on the simulation of DTE test of annealed OFHC copper - at impact velocity ranging from 350 up to 420 m/s - using the modified Rusinek-Klepaczko model, are presented. Simulation of microstructure evolution was performed using the visco-plastic self consistent model (VPSC), providing, as input, the velocity gradient history obtained with FEM at selected locations along the axis of the fragment trapped in the extrusion die. Finally, results are compared with EBSD analysis.

INTRODUCTION

Advanced design of components operating under extreme conditions requires sophisticated material modelling capable to account for deformation and failure mechanisms occurring at different time and length scales. Among available material models, physically-based constitutive models are obtained from the description of deformation mechanisms occurring at different temperature and strain rate for a given microstructural state [1]. Usually, such type of models, if compared with simpler phenomenological constitutive equations, require a larger number of material parameters to be identified although they perform better in predicting material response under wider combination of strain, strain rate and temperature. Characterization tests, such uniaxial tensile and compression test, are usually not sufficient for model validation because only limited ranges of strain, strain rate and pressure can be investigated with such type of tests. Alternatively, the use of so-called "validation" test has been proposed [2]. In this type of tests, the material is subjected to complex deformation processes in which stress, strain rate, pressure, etc. are of the same order of magnitude of those of interest although they cannot be controlled during the test. Probably the best example of validation test is the Taylor anvil impact test [3]. In this test, a cylinder, made of the material of interest, is impacted against a rigid anvil at prescribed velocity. Several quantities (i.e. deformed profile, final length, bulge diameter, final volume, etc.) can be measured on recovered samples and used either for model validation or, more often, for

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calibrating material model parameters [4]. The fact that a material model is capable to reproduce selected test metrics is not conclusive about its ability to describe the material response under general loading conditions. Further validation can be performed showing that computed deformation histories would lead to the same microstructure and texture evolution observed in experiments. In this work, the dynamic tensile extrusion (DTE) test was used as validation test for material modelling. Validation was performed at both macro and microscopic scale. At the continuum scale, the shape, size and number of extruded fragments were selected as validation metrics. Model predicting capability was validated for different impact velocities. Successively, for a reference impact velocity, the deformation histories at selected locations, along the axis of fragment that remains in the extrusion die, were extracted and used as input for texture evolution simulation using the visco-plastic self-consistent model VPSC. Finally, calculated textures were compared with quantitative EBSD analysis results.

APPROACH

The following approach to material model validation is proposed. Firstly, a material model was selected and model parameters were identified only by characterization tests such as quasi-static and dynamic uniaxial traction or compression at different strain rates and temperature. Identification was performed by FEM-based inverse calibration procedure having as objective the test global response (i.e. applied load vs displacement curve). Successively, the model was used to predict material response in selected validation tests. Here, Taylor anvil impact test was used to calibrate further model parameters while DTE test was used for validation only. In the specific, validation was carried out comparing the number, shape and size of the extruded fragments at different impact velocity. Since the numerical simulation of this type of test involves computational issues that may affect the solution, a sensitivity analysis on the effect of numerical parameters such as friction coefficient, mesh size, damping, etc. have to be performed [5]. Provided that the agreement at continuum scale is satisfactory, the velocity gradient as a function of time at selected locations can be extracted and used as input for the VPSC model [6] that returns the texture evolution as a result of the deformation process. Finally, calculated texture maps are compared with EBSD analysis results. This procedure allows correlating microstructural investigation results with computed quantities at continuum scale (i.e. strain, stress and temperature).

MATERIAL AND TESTING

The material under investigation is half-hard OFHC high purity copper (99.98%). The material was fully annealed for 1 hour at 400°C in oven with inert atmosphere. The final grain size measured with the intercept method was 47μm (14μm considering twin boundaries). The initial microstructure showed a random texture containing numerous annealing twins (Fig. 1 and Fig. 2).

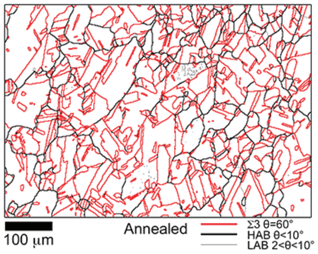

FIGURE 1. Grain structure from the EBSD investigations of the annealed sample.

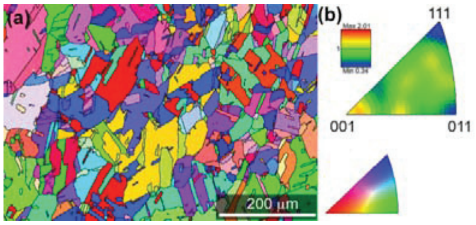

FIGURE 2. Inverse pole figure map (a) and pole figure (b) for the annealed material.

Dynamic tensile extrusion (DTE) tests were performed at 350, 380, 400 and 420 m/s. The geometry of the extrusion die geometry is the same as proposed by Gray III et al. [7] while the projectile has the same mass but bullet shaped (half sphere) with 7,62 mm diameter. Tests were performed using a single stage light-gas gun in vacuum and fragments were soft-recovered in ballistic gel. Fragments size and shape were measured. For the 400 m/s test, EBSD analysis was performed in five selected locations along the symmetry axis of the fragment that remains trapped in the extrusion die.

CONSTITUTIVE MODEL AND NUMERICAL SIMULATION OF DTE TEST

The selected constitutive model is the modified Rusinek-Klepaczko model [8]. The model assumes that the stress is given as the sum of athermal, thermally activated and viscous drag contributions. This model formulation was further extended by Bonora et al. [5] to account for Hall-Petch effect on athermal stress, saturating viscous drag at high strain rate, pressure effect on the melting temperature, and stress saturation at large plastic deformation (hereafter indicated as MRK2). Details on model derivation, equations and parameter identification procedure is given elsewhere [5]. The model was implemented in the commercial finite element code MSC MARC v2014. Since the axial symmetry is maintained during the entire deformation process, the test was simulated using four node isoparametric elements in axisymmetric formulation. The DTE test was simulated performing coupled thermomechanical dynamic transient analysis using Lagrangian upgrading and multiplicative decomposition (F^eF^p) using the radial return method and the three field variational principle. The extrusion die was simulated as deformable body considering contact with friction between the projectile and the die. Since the projectile undergoes extremely large plastic deformation, a global remeshing technique was used to avoid excessive element distortion and convergence issues. Afore, sensitivity analysis on the mesh and other numerical parameters (damping, friction, contact algorithm, etc.) effect was performed. In Fig. 3 a global comparison of the predicted fragment formation with experiment is shown. Here, color contours are indicative of plastic strain (blue 0.2 red >5.0). In Fig. 4 the quantitative comparison of the predicted fragments size for the reference impact velocity of 400 m/s is given. Here other results not considering some of the model features are also shown. For all the cases the agreement with the experimental data is quite good. However, results obtained accounting for pressure effect on the melting temperature seem to provide an overall better agreement. Even if fragments are slightly shorter than that observed experimentally, their shape is predicted more accurately, [5].

Finally, in Fig. 5 the errors between the measured and predicted lengths for each fragment are given. The error increases at higher velocity and this fact can be explained by occurrence of dynamic recrystallization (DRX). In fact, evidence of DRX at 400 m/s was reported in [9], and at 420 m/s DRX is expected most extensive. Since MRK2 does not account for DRX effects on the material behavior, the numerical model is less accurate at higher velocity.

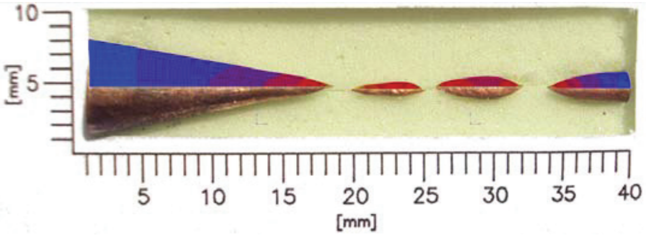

FIGURE 3. Qualitative comparison of FEM and experimental fragment number and shape for 400 m/s impact.

TEXTURE SIMULATION AND RESULTS

VPSC was used to simulate texture evolution under prescribed deformation paths. The VPSC code is a multipurpose polycrystal plasticity research code, based on slip and twinning active in single crystals of arbitrary symmetry. Hörnqvist et al. [9] showed that all points along the axis of the fragment that remain in the die undergo the same deformation path allowing the possibility to probe the material at different deformation level simply looking at different locations. Based on this, histories of the velocity gradient at five selected locations along the axis of this fragment for the 400 m/s impact were extracted from FEM simulation and used as input for VPSC calculation. Texture simulations have been performed considering 500 grains initially randomly oriented. Since the grain are subjected to fragmentation as a result of the large plastic deformation, a critical aspect ratio of 16:1 (that was observed with EBSD) was used as criterion.

In Fig. 6 the regions of texture observations are given. The comparison of the calculated texture with EBSD analysis is shown in Fig. 7. The calculated maximum plastic strain reached at each location is also given. Calculated textures are in a very good agreement with experimental finding for all location except for the point closest to the tip of the fragment. This is justified by the occurrence of dynamic recrystallization (DRX) that is not accounted for in the VPSC code. Actually, DRX starts to occur at location 3 and leads to complete dynamically recovered microstructure in location 5 of the fragment.

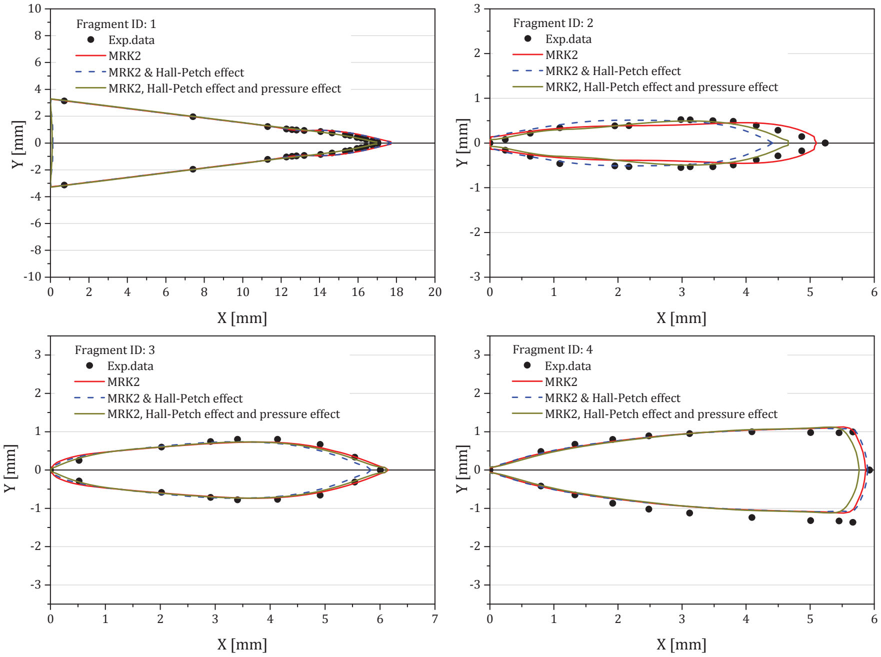

FIGURE 4. Quantitative comparison of fragment size and shape for 400 m/s impact.

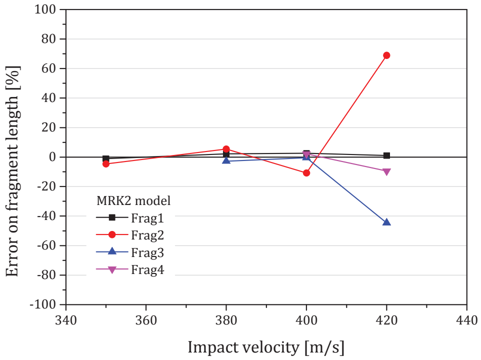

FIGURE 5. Validation of MRK2 model at different velocity: error on measured fragment length.

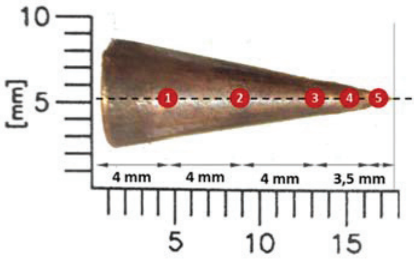

FIGURE 6. Regions of texture observations.

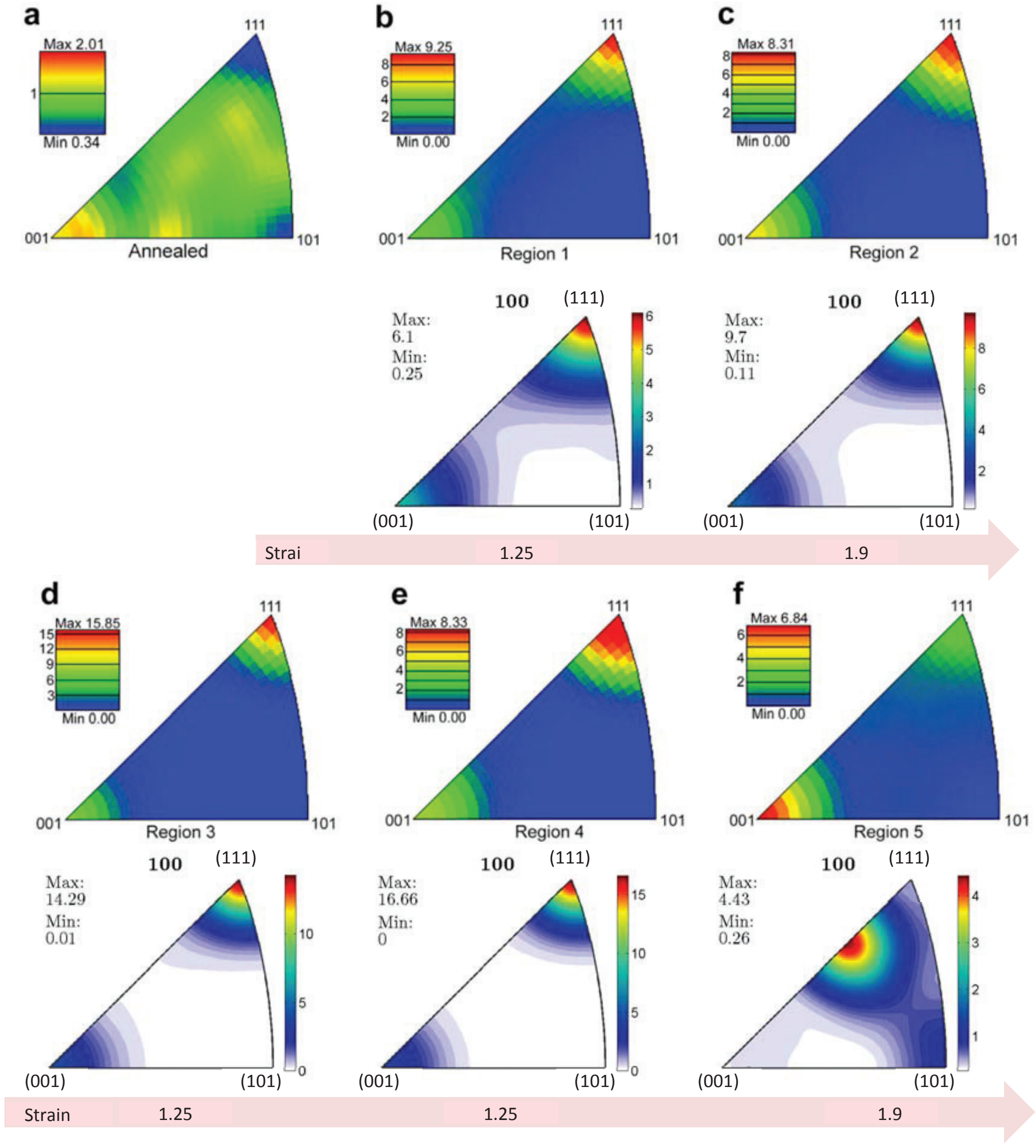

FIGURE 7. Comparison of calculated and EBSD measured texture for selected location along the symmetry axis of the fragment trapped in the extrusion die.

CONCLUSIONS

In the present work, a two-length scale approach for constitutive model validation is presented. In particular, the use of the dynamic tensile extrusion (DTE) test as validation tests is proposed. This test not only allows to probe the material under very large strain, high strain rates and pressure but it allows to extract information about texture evolution at different plastic strain level under the same deformation path (that is, same Zener-Hollomon parameter). Once validated by comparison with available metrics, finite element simulation can be used to extract the velocity gradient histories to be used as input for VPSC calculation and texture prediction. Present results indicate that with MRK2 it is possible to predict accurately the number, shape, size of extruded fragments and texture evolution in DTE test. The agreement is very good in general unless other mechanisms such as DRX come in to play.

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