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THERMO-MECHANICAL FINITE ELEMENT SIMULATION OF HIGH STRAIN RATE TENSILE TESTS ON HIGH DEFORMATION PLASTIC SHEET MATERIALS

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Summary. *Results of coupled thermo-mechanical, dynamic simulations of Split Hopkinson Tensile Bar experiments using the finite element program ABAQUS/explicit are presented. The simulations provide detailed information on the distribution and evolution of the temperature, the stress and the strain in high deformation steel sheet specimens. The simulations allowed validation of the classical assumptions of Hopkinson experiments, and assessment of the influence of deviations from these assumptions on the material behaviour extracted from the experiment. Different specimen geometries are considered.*

1 INTRODUCTION

In order to get a deeper insight into the impact-dynamic behaviour of materials and structures, the identification of dynamic material properties is essential. In the range of medium and high strain rates (from 100 to 5000 s^{-1}) Split Hopkinson bar setups (or Kolsky apparatus[1]) are frequently used to characterize these parameters. The concept of the split Hopkinson bar setup and the basic principle of interpretation is most often used for compression testing, although, with some adaptations, dynamic tensile tests, Split Hopkinson Tensile Bar (SHTB) experiments[2], are also possible. To characterize sheet materials, such as the sheet steels used by the automotive industry, SHTB experiments are obvious.

It is generally assumed that Hopkinson experiments yield the high strain rate *material* behaviour. However, it is observed that changes in the specimen geometry give rise to distinct differences in established mechanical behaviour: thus, a structural and not a material response is obtained[3]. Classical, experimental measurement techniques do not provide sufficient information to fully understand this phenomenon.

During the short (generally less than 1 millisecond) duration of a SHTB experiment, deformation mechanisms in the specimen material result in an adiabatic temperature increase. As a result, the classically observed strain rate hardening in metals will be opposed by thermal softening. Additionally, for some materials the temperature increase can also change the deformation mechanisms in the material. This is for example the case for TRansformation Induced Plasticity (TRIP)steels, where the transformation of austenite will be suppressed. An accurate assessment of the evolution of the temperature field in the specimen is thus fundamental for an in-depth understanding of the material behaviour.

To gain insight into the influence of the specimen geometry and temperature, the authors have performed a series of numerical simulations. Valuable and additional information on the real stress, strain and temperature distribution in the tested material is obtained. The simulations allow assessment the influence of the specimen geometry on the obtained results and validation of assumptions on which the interpretation of the test results is based.

2 SPLIT HOPKINSON BAR EXPERIMENTS

During a SHTB experiment a small dogbone-shaped specimens, sandwiched between two long bars (figure 1), is subjected to a dynamic tensile load. The interpretation of the experiments is based on two essential assumptions concerning the stress state in the specimen. First, stresses are considered to be purely uniaxial; non-axial stresses are neglected. Secondly, the specimen is assumed to be in quasi-static equilibrium, and stresses are consequently homogeneous in the central zone of the specimen. To calculate the strain in the specimen, it is additionally assumed that all deformation is concentrated in the central zone of the specimen (see figure 2). If all assumption are fulfilled, the stress, strain and strain rate in the specimen are obtained independently of each other, without any previous assumption to be made on the mechanical behaviour of the specimen material.

The specimen geometry used in this study consists of a central zone with a constant width and a certain length, and, on both ends of the central zone, transition zones where the width gradually increases following a circular curve. The dimensions of a reference geometry are established based on geometries described in literature: the length of the central zone is 5 mm, the width of this zone is 4 mm, and the radius of the transition zones is 2 mm. Starting from that reference geometry, six additional geometries are determined by varying the radius of the transition zones, the length and the width of the central zones.

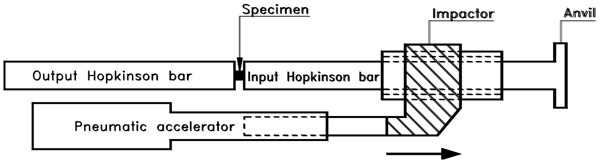

Figure 1: Experimental setup of a typical split Hopkinson tensile bar device

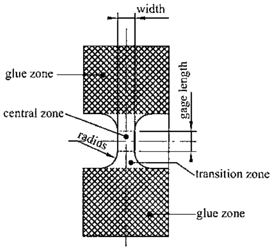

Figure 2: Dogbone-shaped specimen geometry

3 FINITE ELEMENT MODEL

The numerical simulations were performed using the finite element program ABAQUS (from ABAQUS, Inc.). The finite element model was created with ABAQUS/CAE. Since we wanted to study the precise dynamical phenomena in the specimen, we used the ABAQUS/Explicit code for the calculations. The interaction of a real wave with the specimen is modeled to correctly take into account inertia and wave propagation phenomena. The model comprises the test specimen and parts of both Hopkinson bars long enough to have no interference of reflected stress waves with the specimen during the time period of interest. Bars of 2 m length were sufficient. Because of the symmetry only one quarter of the cross-section was modeled. The element mesh for the specimen in the figure comprises 14060 nodes and 10528 elements. Each of the Hopkinson bars accounted for approximately 34005 nodes and 25957 elements.

For the specimens the Johnson-Cook plasticity model, taking into account both the strain rate and the temperature, was used to describe the material behaviour. The model parameters were determined based on static and dynamic experiments on an Al-TRIP steel.

The local temperature rise due to the adiabatic heating is calculated directly from the rate of inelastic energy dissipation and the specific heat and density of the material. We assumed that all inelastic energy is converted to heat. Because of the very high strain rates and short duration of the loading history, no heat transfer between elements needs to be considered.

4 NUMERICAL RESULTS

4.1 Stress, strain and temperature development in the specimen

Concerning the response of the specimen to the high strain rate tensile loading, four distinct phases can be distinguished based on the mechanisms governing the specimen deformation:

- *elastic phase*: from the onset of loading, stresses and strains in the specimen are reversible until at a certain moment plastic deformation starts. No heat is developed in the material. For all geometries, the elastic limit is initially exceeded at the outside border of the transition zones, close to the central zone,
- *early stage of plastic deformation*: very soon after the onset of plastic deformation at the border of the transition zones, yielding also starts in the center of the specimen. The geometry with a length of the central zone of 10mm is an exception: here yielding in the central zone starts in two points a certain distance away from, but symmetrical around, the center of the specimen. Both the plastically deformed zones in the transition zones and the one in the central zone propagate and finally merge to constitute one zone of plastic deformation. Where plastic deformation occurs, the temperature of the material increases (see figure 3, for geometry 1),
- *stable yielding*: one zone of plastic deformation spreads towards the specimen/bar interfaces,

- *unstable yielding*: in this final stage deformation will localize in a zone around the middle of the specimen. In this zone the temperature will increase very fast. However, since softening of the material is not included in the material model, only the start of this final stage is correctly predicted by the simulation.

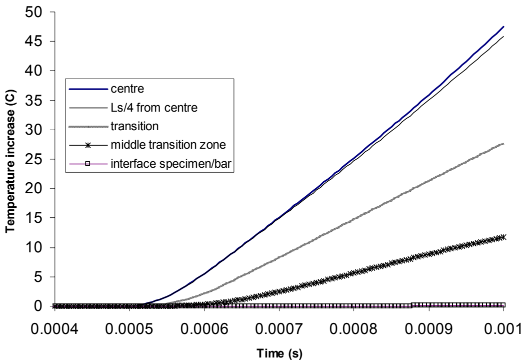

Figure 3: Time evolution of the temperature increase in 5 points on the specimen axis of the reference geometry

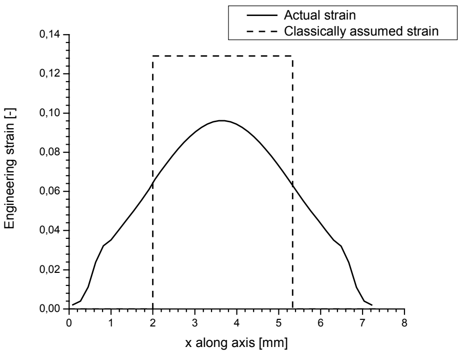

Figure 4: Assumed strain and actual strain along the axis of specimen 6

4.2 Classical assumptions

The numerical simulations clearly show that the classical assumptions, on which the interpretation of the experiments is based, are not fulfilled: 1) non-axial stresses exist in the specimen, 2) stresses and strains are not homogeneous in the central zone (figure 4, for a geometry with a length of the central zone equal to 3.33mm) and 3) the deformation of the transition zones of the specimen is non-negligible. Both the deviations from the classical assumptions and the consequences for the 'material' behaviour extracted from the experiments are strongly dependent on the specimen geometry.

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