Prediction of fracture in the shearing process using DEFORM and MARC software

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Abstract. The aim of this study is the evaluation of the parameters for the material model description in simulation of plasticity and fracture in shearing processes. The experimental measurements and the simulations are performed at room temperature for TWIP steel and 38MnVS6. The behaviour of materials is described using MARC/MENTAT and DEFORM software based on the finite element method. The material model is made up on the basis of tension test. The fracture criteria are based on the experimental failure during tension and torsion tests. The fracture models Normalized Cockcroft-Latham (NCL) and Oyane are used for subsequent simulation of shearing. The description of shearing comprises not only the initiation of a fracture but also the growth of the fracture until the material parts are separated. This issue is solved by means of two numerical methods, the softening and the element deletion.

1 Introduction
The finite element method (FEM) is widely used numerical methodology for the analysis of arbitrary metal forming processes. A numerical model for shearing process involves equations for accumulation of critical level of damage which lead to the initiation and the growth of a fracture in the workpiece. The prediction of a fracture in shearing process is analyzed in DEFORM and MARC software. The validation of accuracy and reliability of used methodology is verified through measurements.

The aim of this work is to describe the process of obtaining critical damage values for simulation of shearing process. Tensile and torsion test are carried out for obtaining the material model. Two damage models (Normalized Cockcroft & Latham and Oyane) for simulation of ductile fracture are used. The empirical hypothesis is that the ductile fracture occurs when the maximum damage value exceed the critical damage value [1]. The shearing simulation is subsequently calculated with the obtained critical damage values. The growth of the fracture in the simulation of shearing operation is ensured by means of two methods. The first method is the softening of material data and the second method is the element deletion. Damage softening is a method by which the flow stress of an element above this critical value will be reduced to a specified percentage. For element deletion, elements which exceed a defined critical damage value are deleted from the mesh in the simulation. The simulated and measured forces are afterwards compared for verification of used method.

The intention of the work is to carry out the sufficiently accurate shearing simulation with the material and damage model from limited amount of experimental input data. This work appends plastic behavior of TWIP steel and 38MnVS6 and its damage critical values into the ductile fracture theory. It is expected that the introduced approach of obtaining data for shearing simulation can be useful for a wide range of application.
2 Material model

The experiments are performed on TWIP steel and 38MnVS6. The chemical compositions of tested materials are listed in Table 1 and Table 2. The material of TWIP steel is provided as rolled sheet with the thickness 8 mm and the samples of 38MnVS6 are in the form of rod with diameter 10 mm.

| C   | Si  | Mn  | P   | S   | Cr  | Mo  | Ni  | Cu  | Al  | As  | B  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|----|
| 0.116 | 1.58 | 15.09 | <0.005 | 0.002 | 0.085 | 0.124 | 0.072 | 0.078 | 0.38 | 0.015 | 0.002 |

| Pb  | Co  | Nb  | Ce  | Sb  | Sn  | Ta  | La  | Ti  | V   | W   | Zr |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|----|
| 0.090 | 0.008 | 0.022 | <0.005 | 0.029 | 0.008 | 0.261 | 0.016 | 0.003 | 0.014 | 0.100 | 0.015 |

Table 1. Chemical composition of TWIP steel.

| C    | Si   | Mn   | P   | S   | Cr  | Mo  | Ni  | Cu  | Al  | As  |
|------|------|------|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.39 | 0.60 | 1.33 | 0.02 | 0.05 | 0.14 | 0.03 | 0.08 | 0.05 | 0.01 | 0.01 |

Table 2. Chemical composition of 38MnVS6

2.1 TWIP steel

The specimens for the tension and the torsion test are made from the tested material. In the case of TWIP steel, the part of the specimen subjected to tension has the length 60 mm, the width 12.5 mm and the thickness 8 mm. An extensometer with 25 mm gauge length is used to measure displacement change of the central part of the sample. This uniaxial tension test is used for obtaining load-displacement curves. The shape of true stress-strain curve up to the ultimate tensile strength is directly calculated from these measured curves. The tension test is simultaneously simulated and the true stress-strain curve is fitted by trial-and-error method until the load data from the experiment corresponded well with the simulation. The temperature of the tested material is 20°C and the rate of the sample holder is 0.05 mm/s. The same conditions set during the experiment are for the simulation. The measured load-displacement curves compared with the fitted data from simulation are presented in Figure 1. The measured length by extensometer elongates almost 9 mm before the fracture started on the sample.

Figure 1. The comparison of measured and simulated tension test (TWIP steel).

Figure 2. The comparison of measured and simulated torsion test (TWIP steel).

The sample for torsion test has the length 190 mm, the width 15 mm and the thickness 8 mm. The part of the sample subjected to torsion has the length 10 mm and the diameter 6 mm. The torsion
test is carried out and simultaneously the simulation of the test is performed with the same process parameters. The rate of rotation is $2^\circ$/s. The material data model for the torsion test simulation is described by true stress-strain curves from the previous tension test. The comparison of measured and simulated torsion test is in Figure 2. The torsion angle of tested specimen is about $300^\circ$ when the fracture appears.

2.2 Material 38MnVC6
The smooth round bar has a diameter of 6 mm and a gauge length of 30 mm. The elongation record is obtained through a mechanical extensometer with the initial length 20 mm, see Figure 3. The extensometer provides the displacement vs. time curve while the machine provides the crosshead displacement and force-time records. Using the ZWICK 200 kN machine, the test is carried out at the speed of 0.033 mm/s. The extensometer measured length elongates 4.7 mm before the fracture. A small-size specimen of 3 mm diameter and 10 mm gauge length is used for the torsion test. The specimen bent slightly during the test, which distorted the test data. Despite that, the torque data calculated from the piston angle appears to be in relatively good agreement with the simulation (Figure 4), showing that the deflection has no major effect. The torsion angle is ca $520^\circ$ before the specimen fractures.

![Figure 3](image1.png)  
*Figure 3. The comparison of measured and simulated tension test (38MnVS6 steel).*

![Figure 4](image2.png)  
*Figure 4. The comparison of measured and simulated torsion test (38MnVS6 steel).*

3 Damage models
Many publications are available about the use of damage criteria [2]-[6]. The prediction of the fracture site and its propagation depends on the working conditions, i.e. deformation history, state of stress, temperature and strain rate sensitivity, etc. The fracture in the tested materials during the shearing process is studied by means of two damage criteria Normalized Cockcroft & Latham and Oyane. Damage is a cumulative parameter which evolves through the history material undergoes and its critical value needs to be determined experimentally through suitable workability tests, under defined and controlled conditions. This study examines a fracture criterion on the basis of tension and torsion tests. The quick drop of the load in the experiment shows the crack formation in the specimen. The simulation of performed tests can demonstrate an effect of the stress and strain growth during tests which lead to the fracture.

In the literature [7], it is described great effect of stress triaxility on fracture behavior of materials. The stress triaxility is defined as:

$$\eta = \frac{\sigma_m}{\sigma_{eq}}$$  \hspace{1cm} (1)

where $\sigma_m$ is hydrostatic stress and $\sigma_{eq}$ is equivalent stress.
The damage criterion by Cockcroft & Latham (in normalized form) is defined:

\[ D_C = \int_0^{\varepsilon_f} \frac{\sigma}{\sigma_{eq}} \, d\varepsilon \]  

(2)

It takes accent on max. principal stress \( \sigma_1 \), it means that the principal stress cause the fracture in the specimen. The value \( \varepsilon_f \) represents the strain in the moment of fracture initiation.

The simulation of tensile and torsion tests were performed in the first iteration without damage fracture, where only cumulation of the damage factor for NCL criterion was calculated. The critical damage value is related to the moment of fracture in the simulation of torsion test which corresponds to the experimental fracture for each tested material. Consequently, the critical damage value was improved by calculation using modification presented in [7] of NCL equation (2).

Oyane damage criterion is based on stress triaxiality, which implicates the initiation of fracture:

\[ D_C = \int_0^{\varepsilon_f} \left[ 1 + \frac{1}{a_0} \frac{\sigma}{\sigma_{eq}} \right] d\varepsilon \]  

(3)

where \( a_0 \) is material coefficient to be determined experimentally.

The calculation of critical damage value for Oyane equation (3) needs to determine two parameters. The reason, why is chosen torsion test, is that the triaxiality of this test is approximately zero which enables simplify the equation: \( D_C \approx \varepsilon_f \). This leads to the equality of critical damage value and the accumulated strain in the simulation of torsion test at the moment of fracture. Second parameter of (3) can be simply calculated by means of the fracture strain and triaxiality obtained from simulation of tension test.

4 Shear test

4.1 TWIP steel

Hydraulic shears is used for cutting of rolled sheets (Figure 5), with maximal hydraulic pressure 26(28) MPa, maximal cutting force 4.5 MN and nominal vertical speed 5 mm/s (35 mm/s with accumulators). For measuring the shear force is used one analogue pressure transducer connected on incoming pipe to IBA system of pilot rolling mill. This configuration allows record the shear force during the test in dependence on time.

Several experimental cuts have been performed using above mentioned “shearing device”. These cuts are numbered on a picture as 6 to 9 number, where cut 6 corresponds to the length of cut 210 mm, cut 8 to 185 mm and cuts 7 and 9 has equal length 63.5 mm.

![Figure 5. Tested rolled sheet.](image)

![Figure 6. 2D numerical simulation of shearing.](image)

The calculated critical damage values for both integral criteria NCL and Oyane are used in the subsequent simulation of fracture during shearing operation. The distribution of damage in the
selected moment is seen in the Figure 6. Shearing operation is calculated using two methods: the softening of material data and the element deletion. Figure 7 shows the comparison of the calculated force from numerical simulation and the measured force.

![Figure 7](image)

**Figure 7.** Measured and calculated force during shearing operation for selected methods.

4.2 Material 38MnVC6

The test is carried out at ambient temperature with the punch speed of 90 mm/s. The shearing die is placed on a plate load cell attached to the frame of an MTS 810 testing machine. The punch is connected to a moving piston and the test specimen of 10 mm diameter is placed into the fixture. The die clearance is 0.05 mm in accordance with the applicable standard. The model of the specimen comprises only one quarter of the actual piece (Figure 8) because of its two symmetry planes. The shear plane has a much finer mesh than the other parts of the model. In the simulation model, the material is considered to be homogeneous, isotropic, and elastoplastic. Its plasticity was characterized by the fitted flow stress curve. The parts of the fixture are considered rigid bodies for the calculation. The distribution of equivalent stress in the selected moment of simulation is seen in the Figure 9. Figure 10 shows the comparison of the experimental forces and calculated force from numerical simulation.

![Figure 8](image)

**Figure 8.** ¼ FEM model for shearing of rod.

![Figure 9](image)

**Figure 9.** FEM simulation.
5 Conclusion
Fracture prediction plays an important role in the description of a shearing process. This study presents the procedure of obtaining critical damage values on the basis of only two experiments. Numerical simulations are performed with the use of uncoupled models, where the fracture is analyzed by combining plasticity and ductile damage. Material plasticity is characterized by flow stress curve obtained from a tensile test. The critical damage value for each material is identified from simulation of torsion test at the moment of fracture which corresponds to the failure during experiment.

The performed technological tests prove the usability of the chosen method of identifying the critical damage values. The measured and simulated data for shearing test were in a quite good agreement. This presented procedure can enable the prediction of forming limits for a wide range of application.

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