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Numerical and experimental determination of cut-edge after blanking of thin steel sheet of DP1000 within use of stress based damage model

Bernd-Arno Behrens, Anas Bouguecha, Milan Vucetic, Richard Krimm, Tobias Hasselbusch, Christian Bonk*

Institute of Forming Technology and Machines, Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany

Abstract

The proposed study focuses on blanking of thin steel sheets of Dogal1000DP +Z100MBO. Numerical and experimental investigations of the influence of clearance and punch speed on the cutting force and the geometry of the sheared edge were done. Tensile and stack compression test at elevated temperatures has been chosen to determine the flow and fracture behavior of Dogal1000DP +Z100MBO at different stress states. It is shown that the flow curve determined by stack compression test leads to better results in force - displacement prediction of a blanking process compared to determination of flow curve by tensile test. Stress based fracture criterion were chosen to describe damage behaviour. Moreover significant influence of fracture locus for negative stress triaxialities on the geometry of the numerically predicted sheared edge is shown.

Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

Keywords: Dual phase steel; Blanking; Damage; FE-simulation; Stack-compression test; Tensile test

* Corresponding author. Tel.: +49-511-762-5550; fax: +49-511-762-3007
E-mail address: bonk@ifum.uni-hannover.de

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1. Introduction

The blanking process is one of the most common sheet cutting processes used in mass industries. As a result of the complexities involved due to the material behaviour (large local plastic deformations, temperatures and high strain rates) of the sheet metal and the process parameters (punch and die corner radii, punch rate, the clearance between the punch and the die), the blanking process is not entirely understood. Therefore, the process design, with an aim to obtain a high quality cut-edge of a blank, is generally based on time-consuming trial and error procedures involving a large number of expensive tests Husson et al. (2008). FEM simulations offer an effective means not only to cost savings and speedup of the industrial production process but also to predict the quality of the cut profile of the blanked products with an adequate accuracy. However, for a realistic simulation of the blanking process, the accurate modelling of the flow behaviour as a function of strain, strain rate, temperature and the damage behaviour under various stress states is essential. Therefore, stack compression test were carried out for the AHSS cold rolled steel sheet Dogal1000DP +Z100MBO at different temperatures to handle large deformations and high strain rates in blanking process. Standard tensile tests were carried out and compared to the stack compression tests. Moreover, the fracture strains for the uniaxial compression and uniaxial tension were determined to parameterize the damage model.

2. Material characterization

The strain-hardening behaviour of the dual phase steel Dogal1000DP +Z100MBO with thickness of 1 mm was determined from uniaxial tensile tests on samples cut from the sheets in a deformation dilatometer BÄHR DIL 805A/D+T. Three tensile specimens were cut from each of the three different directions (0°, 45° and 90°) using water jet machining. Force versus displacement was recorded during each of the 12 uniaxial tension tests. Stack compression test was carried out to determine the hardening behaviour under uniaxial compression in an INSTRON 400 kN universal testing machine. Moreover stack compression test has capability of evaluating material response to much larger strains than in tensile tests, due to the absence of necking, in conjunction with the aptitude to simulate more precisely the operative conditions of real blanking processes, which is carried out at high compressive loads und large strains. To avoid frictional effects between the faces of the specimen and the compression plates, the test pieces are coated with MoS_2 lubricant. The recorded force-displacement data averaged over three specimens in each of the three directions for the tensile test is shown in Fig. 1a. Tests in the same direction were very repeatable. The onset of necking for each test is indicated in Fig. 1a. The true necking strain was found to be ε_n= 0.049 and strain at fracture was ε_f= 0.14. To evaluate the temperature influence, uniaxial tensile tests at 20 °C, 150 °C, and 300 °C were carried out (Fig. 2a and Fig. 2b).

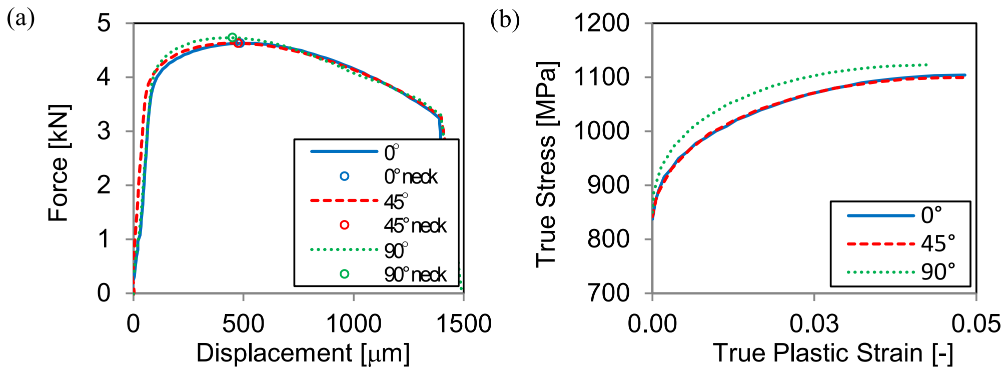

Fig. 1. (a) Force vs. displacement measured in uniaxial dog-bone specimens (gauge length = 10 mm) for different directions (0°, 45° and 90°) and strain rate 1 1/s. (b) True stress vs. true plastic strain calculated up to necking for different directions (0°, 45° and 90°) and strain rate 1 1/s.

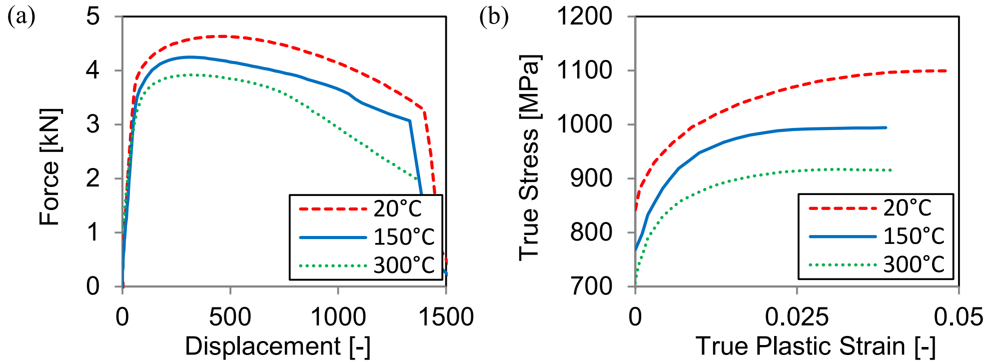

Fig. 2. (a) Force vs. displacement measured in uniaxial dog-bone specimens (gauge length = 10 mm) for different temperatures (20 °C, 150 °C and 300 °C) and strain rate 1 1/s. (b) True stress vs. true plastic strain calculated up to necking for different temperatures (20 °C, 150 °C and 300 °C) and strain rate 1 1/s.

The strain rate sensitivity was determined with the help of the stack compression tests at average engineering strain rates of 1 and 10 1/s. Moreover, the temperature influence was evaluated at 20 °C and 150 °C in stack compression test (Fig. 3a). The curve extrapolations of the tensile test according to Ludwig are shown in Fig. 3b. In comparison to the stack compression test it can be seen, that with increase of strain difference of yield stress becomes greater.

Table 1. Ludwik coefficients

Temperature (°C)	a (MPa)	n (-)
20	1331	0.0604
150	1269	0.0656
300	1204	0.0716

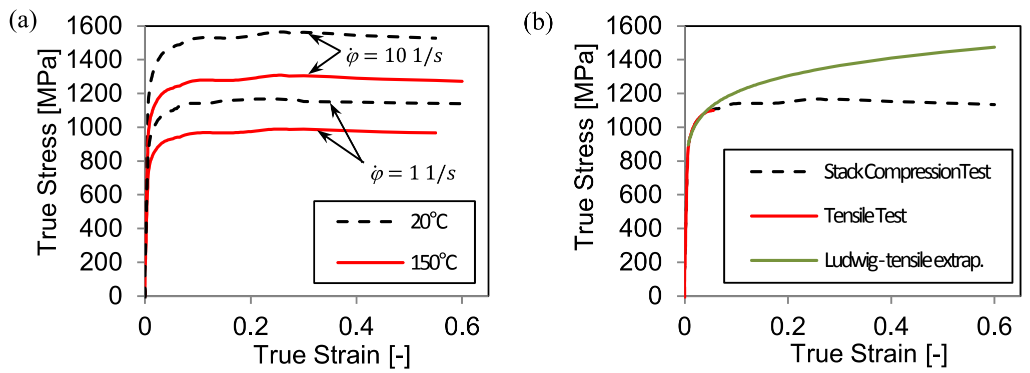

Fig. 3. (a) True stress vs. true strain measured in the stack compression test for different temperatures (20 °C and 150 °C) and strain rate 1 1/s and 10 1/s. (b) True stress vs. true strain measured in tensile and stack compression test for 20 °C and strain rate 1 1/s and curve extrapolation of tensile data according to Ludwig approach.

3. Experimental investigations of blanking

Blanking experiments were performed on Haulik Roos automatic punching press at IFUM with stamping speed of 25, 60 and 170 mm/s and a relative clearance of 5 %, 10 % and 15 %. The punch forces versus time as well as the cutting edges were measured. The results for the force versus time are shown in Fig. 7. In contrast to the flow behaviour (which shows a definite dependence on the strain rate and temperature) it is clear seen that the stamping speed as well as the relative clearance do not influence the maximum punch force. One possible explanation for these observations could be that the temperature increase in shearing zone leads to a significant decrease of yield stress. The cutting edges were measured with a laser measuring method developed at IFUM Behrens et al. (2014). For a statistical coverage of measured results shearing edge was analyzed on four different points along circumference. Generally the shearing zone is defined in four zones, the rollover, the shear, the rupture zone and the burr. As the clearance increases, the rollover depth increases due to the growth of the bending moment in the blank on the tool cutting edge. The ratio of the shear zone height decreases with an increasing clearance and the rupture-zone increases. The burr formation disappears with a selection of small clearance.

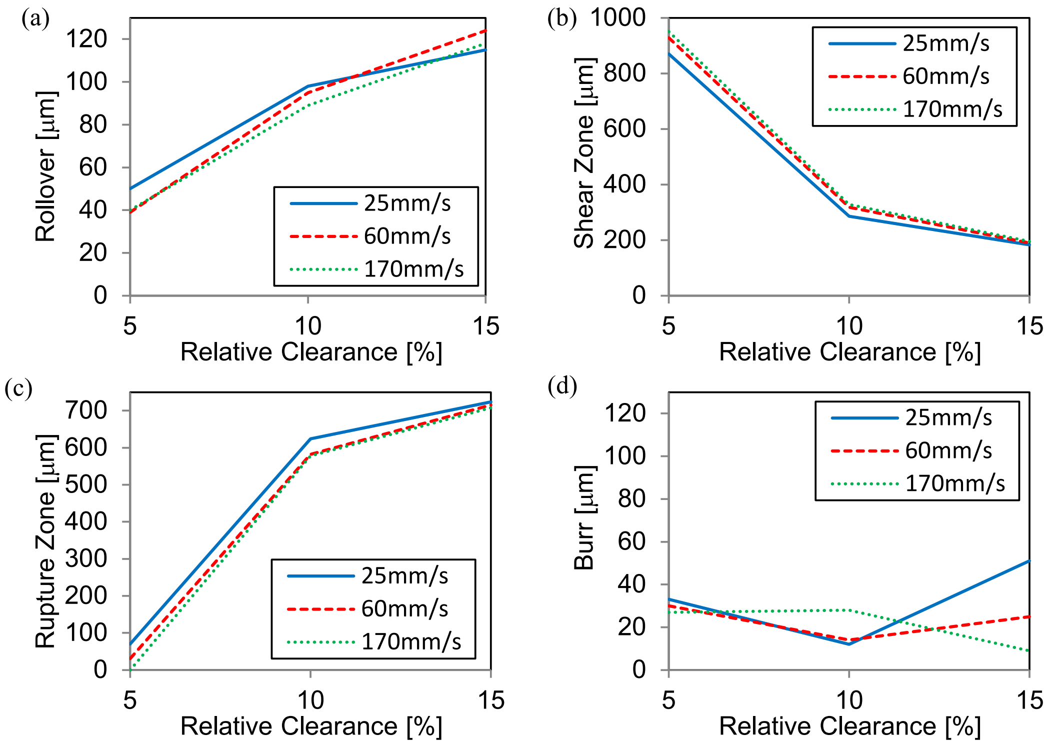

Fig. 4. (a) Experimental results for the rollover vs. rel. clearance. (b) Experimental results for the shear zone vs. rel. clearance. (c) Experimental results for the rupture zone vs. rel. clearance. (d) Experimental results for the burr vs. rel. clearance.

4. Numerical investigations of blanking

For numerical modelling ABAQUS/Explicit was used. The geometry of the tools and the mesh are shown in Fig. 5. The tools were assumed to be rigid bodies and the main geometrical conditions are summarized in Tab. 2. The workpiece is modeled with the combination of axisymmetric elements CAX4R (rectangular) with reduced integration scheme and the hourglass control. Due to axialsymmetry, only a half of the problem is analyzed. In the shearing zone, the mesh size is kept to 10 µm. For the modelling of contact penalty method was used between the tools and the blank and a hard contact was defined as well as a friction coefficient of 0.1. As shown in Bao et al. (2008), Behrens et al. (2011), Johnson et al. (1985) for various steels a characteristic plastic strain at fracture vs. stress triaxiality relationship can be found, meaning that for high stress triaxility plastic strain to fracture decreases. Bao and Wierzbicki (2004) presented a fracture criterion that applies compression through to plane-strain tension. It assumes that fracture does not occur in compression beyond the uniaxial case and fracture between this and shear is modelled as a power law. The ranges of shear to uniaxial tension and uniaxial tension to plane-strain are parabolic curves. In contrast to this, the stack compression test shows that under uniaxial compression case shear damage occurs for ε_f= 0.64 (Fig. 6a). In order to find the best damage model for blanking, Bao-Wierzbicki model and a modified model (shown in Fig. 6b) were used and compared to the experimental results.

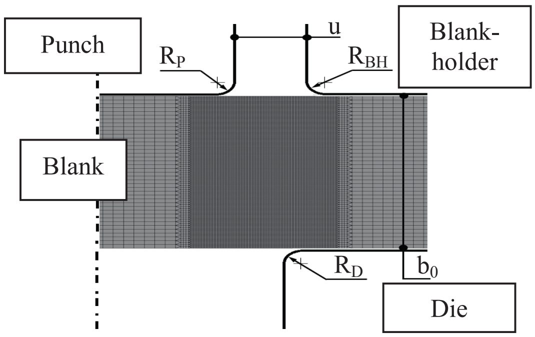

Table 2. Model geometries

punch diameter (mm)	R_{BH}, R_D, R_P (µm)	u/b_0 (%)	b_0 (mm)
35	10	5; 10; 15	1

Fig. 5. Schematic representation of the cutting geometries and the model mesh

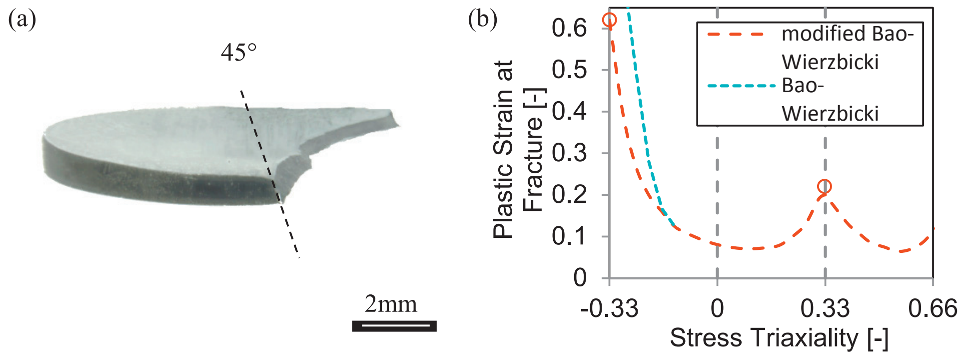

Fig. 6. (a) Shear failure for ε_f= 0,64. (b) Fracture curve for Bao-Wierzbicki (blue) and modified Bao-Wierzbicki (red) model.

Figure 7b shows the force versus time calculated by FE-simulation for yield curve determined by stack compression test. As these curves show, there is a good agreement with the experimental results. Figure 7a shows the force versus time predicted by FE-simulation for flow curve predicted by tensile test and extrapolated according to Ludwik. It can be seen, that the yield curve predicted by the tensile test and extrapolated according to Ludwik leads to higher punching forces. This means that the yield curve determined by the tensile test and extrapolated by Ludwig brings insufficiently accurate results and if the tensile test only is available another extrapolation approach should be used.

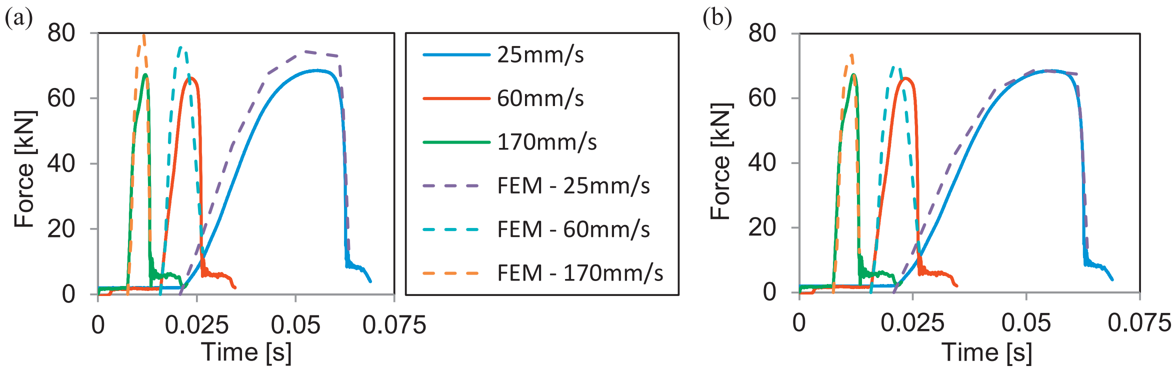

Fig. 7. (a) Experimental and numerical determined force versus time in blanking process for different stamping speeds (25 mm/s, 60 mm/s, 170 mm/s) and relative clearance of 5% with yield curve determined by tensile test and extrapolated according to Ludwik and (b) with yield curve determined by stack compression test.

Fig. 8a-d shows the height of the zones versus rel. clearance predicted by FE-simulation with standard fracture curve and modified Bao-Wierzbicki fracture curve for punch speed of 25 mm/s. As these curves show, there is a good agreement with the experimental results. Moreover it is shown, that the modification of the fracture curve by setting the plastic strain at fracture for the uniaxial compression case to fracture strain determined in stack compression test leads to some improvement of the fracture initiation and the predicted shearing edge.

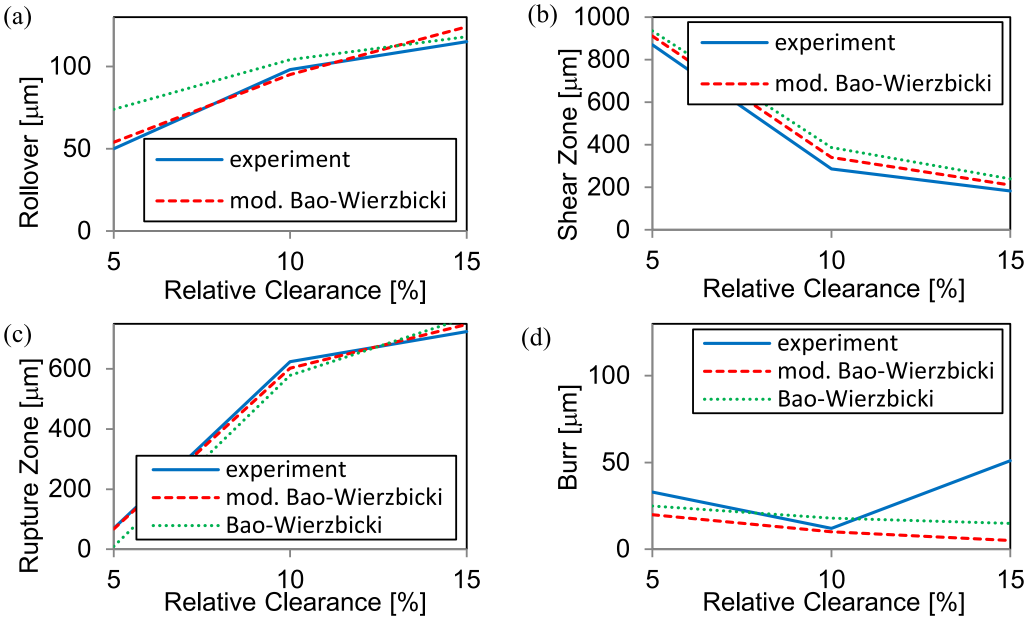

Fig. 8. Experimental and numerical results for (a) rollover versus clearance (b) shear zone versus clearance (c) rupture zone versus clearance (d) burr versus clearance for punch speed of 25 mm/s.

5. Conclusion and Outlook

Though it was shown, that force versus time can be accurately predicted with the flow curve determined by a stack compression test. If only a tensile test is available Ludwig extrapolation brings insufficiently accurate results and another extrapolation should be used to handle high plastic strains. The modification of the fracture locus for negative stress triaxialities leads to some improvement of the determined sheared edge. Moreover, experiments show that velocity of punch does not influence the punching force. One possible explanation could be that the temperature increase in shearing zone leads to significant increase of yield stress and quasi adiabatic conditions. In the future further investigations should be carried out to determine real temperature field in shearing zone. The authors thank the DFG (German Research Foundation) for the financial support of the project “Experimentelle Analyse und Entwicklung eines Finite Elemente Modells zur verbesserten numerischen Abbildung des Scherschneidprozesses” (BE- 1691/133-1).

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