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Determination edge strain for fracture prediction of cut edges in sheets made of DP1000 and DC01 steel

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Abstract. Sheared edge quality is a critical variable with respect to the risk of free edge cracking, most notably in advanced high-strength steels (AHSS), which continue to replace conventional steels in automotive industry applications. This paper deals with finding the edge strain limit for edges of different finish qualities. The edge quality is crucial to preventing free edge cracking in deep drawing operations. Therefore, the purpose of this paper was to determine the limit strain which leads to cracking in free edges produced by different sheet parting methods. The variables were the blanking method and the sheet material. Sheared edges and machined edges were produced in conventional DC01 steel and DP1000 AHSS steel. A special fixture was used for measuring the strain level. The strain values were then input into an FE analysis performed using AUTOFORM code for the purpose of their validation. The physical qualities of these edges were compared using a special test procedure, the Diabolo test, which was introduced by Held [1] and Liewald and Gall [2]. In this test, the edge is subjected to loading under plane strain conditions. Another method of testing the susceptibility to edge cracking is the hole expansion test [4], which induces cracking along a circular hole in the centre of a part. The limit edge strain can be derived with the aid of DIC optical-measuring system which monitors strain increments in the course of the test. Factors which affect the susceptibility to edge cracking were identified and validated for DP1000 and DC01 materials

Introduction

In recent years, several approaches have been developed to predict the formation of a free-edge curve by numerical simulation [1]. They share the use of FLC as the basis for calculating reduced forming ability. These models require experimental data obtained from the most commonly used tests for this purpose and hole expansion test according by ISO 16630. In this test, the hole is extended by a conical piston until it breaks in its circumference. The evaluation criterion is defined as the ratio of the extension of the opening between the original diameter and the fracture size. However, this test does not provide the maximum strain value, which is achieved before crack formation. Therefore, several alternative tests [6] have been developed to measure this value. In the present article, the so-called Diabolo test described by Held [1] was used and DC01 steel was analyzed. The susceptibility of the sheared edge was tested on three series of test specimens. Each series was produced by a different cutting method: shearing, chip cutting, and laser cutting. Each specimen has a size of 40×200 mm. The Diabolo test set-up involved optical measurement. Thanks to special punch geometry, the strain was localized into a small region adjacent to the sheared edge. This strain can be measured by GOM Aramis strain measurement system. In this study, the maximum major strain $\varphi1$ before cracking was evaluated to characterize the edge crack sensitivity. The moment of necking was detected by a time-dependent approach similar to the approach suggested by Volk and Hora for the Nakazima test [5].

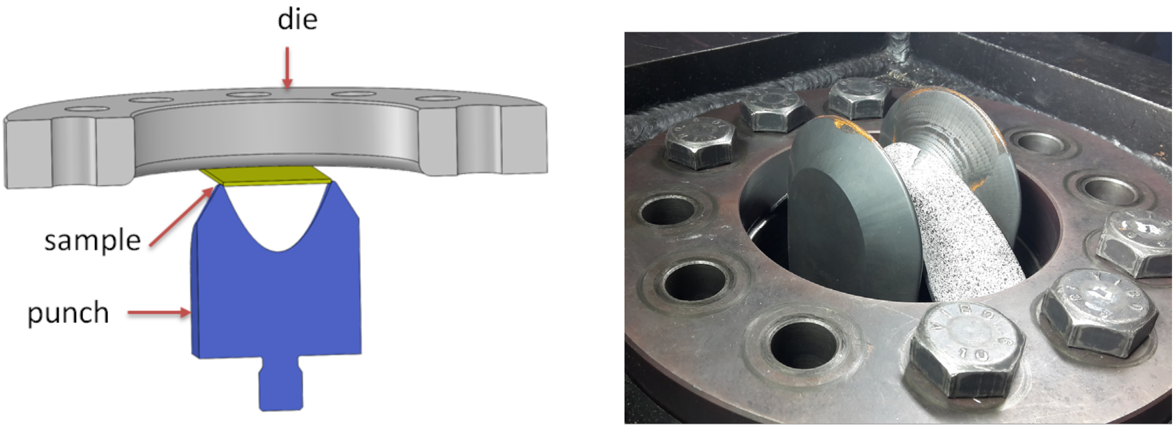


Fig. 1: a) Configuration of tools and sample before forming, b) Sample after measurement

Experimental material and method

Deep-drawing steels exhibit a purely ferritic structure, or consist of a ferritic matrix, in wihich isolated pockets of grain carbide can be embedded, see Fig.2 a). DP steels consist of a ferritic matrix containing a hard martensitic second phase in the form of islands see Fig.2 b). Increasing the volume fraction of hard second phases generally increases the strength. DP (ferrite plus martensite) steels are produced by controlled cooling from the austenite phase (in hot-rolled products) or from the two-phase ferrite plus austenite phase (for continuously annealed cold-rolled and hot-dip coated products) to transform some austenite to ferrite before a rapid cooling transforms the remaining austenite to martensite. Due to the production process, a small amount of other phases (bainite and retained austenite) may be present. A commercial AHSS steel sheet grade DP1000 with the initial thickness of 0,8 mm was used in this work. When these steels deform, strain is concentrated in the lower-strength ferrite phase surrounding the islands of martensite, creating the unique high initial work-hardening rate (n-value) exhibited by these steels. Fig. 1. is an actual micrograph showing the ferrite and martensite constituents. DC 01 is construct low carbon steel. Diabolo test was performed using our Nakazima test machine [7], but the classic spherical punch was replaced by a diabolo punch. All measurement and evaluation methodology was based on ISO12004, which describes the determination of the FLC curve from measurements. ARAMIS DIC system and the time dependent method described by prof. Hora were used for online measurement and evaluation. The measurement procedure consisted of assembling and calibration of the setup, measurement, evaluation and processing of the measurement, and finally application in FEM software.

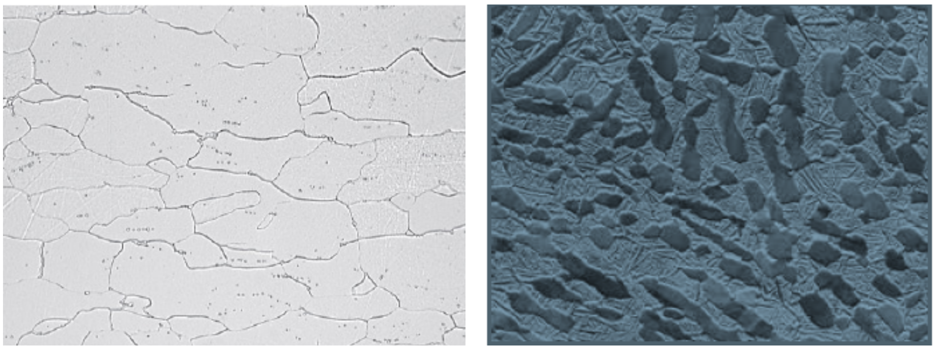

a) b)

Fig. 2 Micrograph of a) deep-drawing steels and b) DP steel

The material model is highly dependent on accurate descriptions of the material´s mechanical behaviour, the selected constitutive model as well as the input data used for its calibration. Therefore, trying to create the appropriate description for the DC01 steel sheet (Tab 1.) and DP1000 steel sheet (Tab 2.), the following material model was selected to describe as accurately as possible the material behaviour based on the hardening law.

Tab. 1: Chemical composition steel DC01

element	C	Mn	P	S	N	Al
%	0.12	0.6	0.045	0.045	0.003	0.04

Tab. 2: Chemical composition steel DP1000

element	C	Si	Mn	Ni	Cr	P	S	N	Al
%	0.16	0,17	2,17	0,01	0,44	0.008	0.003	0.003	0.039

The plastic true stres-strain curves gathered from tensile test are illustrated in Fig. 2.

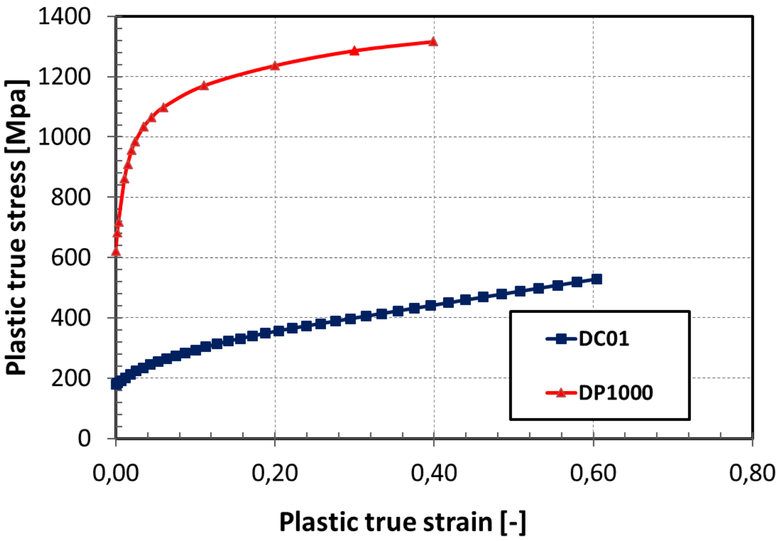


Fig. 3 Plastic true stress-strain curves of steel grade DC01 and DP1000

The shear cutting procedure can be defined as two edges working towards each other to separate material into smaller pieces. The material between the edges is deformed so that fractures appear and eventually the material will separate. Material properties such as strength, Young's modulus and ductility have great impact on the cutting procedure. When the two edges engage in the material, see Fig 3, a fracture will appear on each side and will continue to grow as the edges continue to move through the material. A basic condition that must be met to perform a shear cutting operation is that the material of the cutting tool needs to have larger hardness and strength than the material to be separated. After a shear cut operation an edge with several different zones appear, see Fig. 2, and due to different adjustments of the cutting tool the length of this zones can vary. With optimal adjustments of the cut tool the shear zone represents between 25-35 % of the edge surface. An edge with a large burr zone is a sign that the adjustment of the shearing tool was suboptimal. For an edge with a big burr zone, the adjustments of the cut tool have not been advantageous.

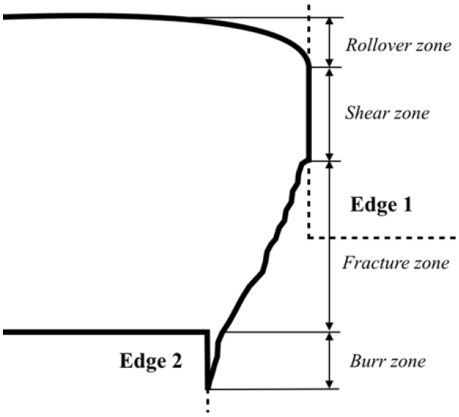


Fig. 4 Zones in a shear cut edge

With the shearing knives appropriately adjusted, the cracks running from both sides meet, resulting in material separation, as in Fig 5. With increasing clearance between or wear in the knife edges, the cracks are less likely to meet. This leads to higher forces needed for separation and poorer quality of the sheared surface. The resultant sheared surface quality can be altered by making changes related to the gap (clearance) between the knife edges, the wear in the knives, the shearing edge geometry and the amount of lubricant.

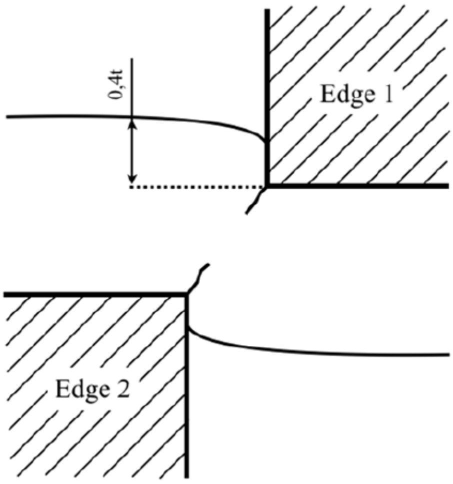
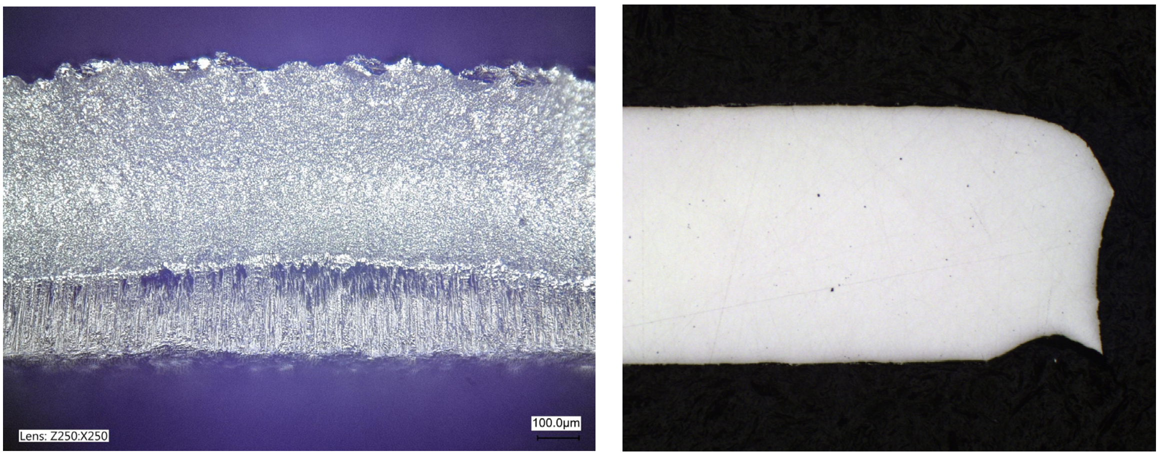


Fig. 5 With optimal adjustments, the fractures will meet and give a fine cut. When the edge advances approx. 40% (0.4t) of the thickness of the material, a fracture will appear.

Sheared edges of specimens

Both specimens were examined under an optical microscope to evaluate the effect of the surface condition on the risk of edge cracking. The edge qualities were analyzed under a microscope and micrographs were taken.

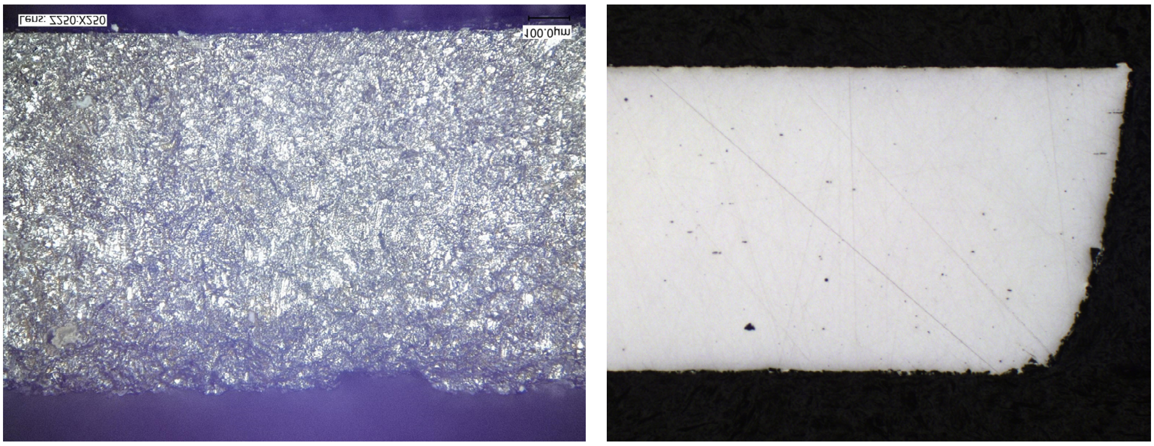
Fig. 6 below shows the quality of the sheared surface in the sheared specimen



a) Sheared surface
b) Cross section through the sheared edge

Fig. 6 Quality of the sheared surface in the sheared specimen of DP1000 steel sheet of 0.8 mm thickness

The figures below document the quality of the edge surface in the machined specimen.

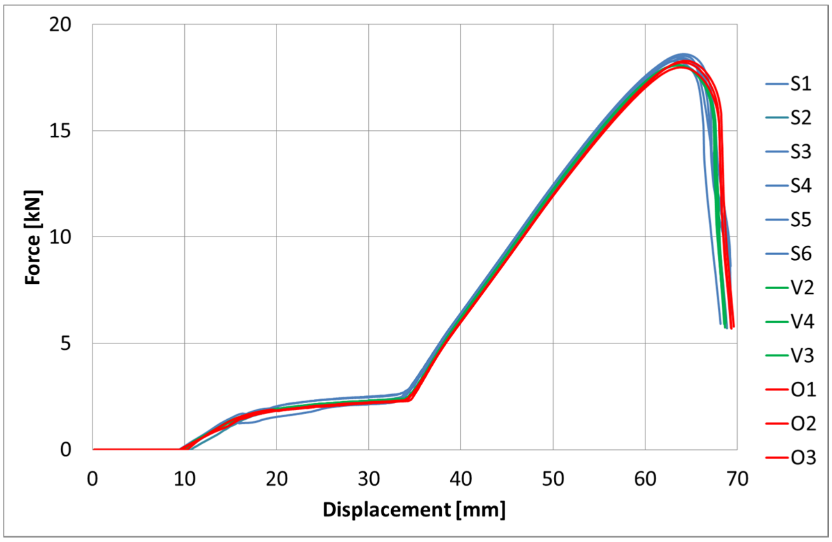


a) Machined surface
b) Cross section through the edge

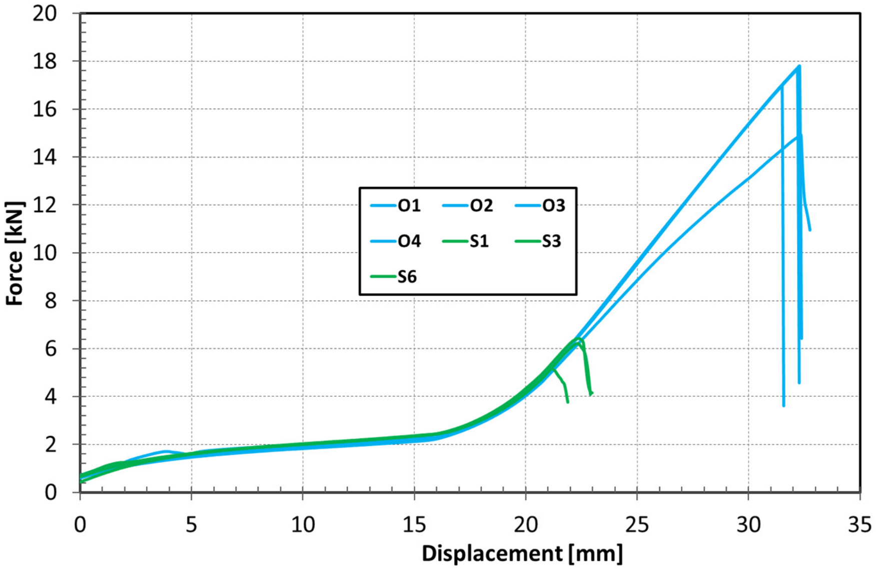
Fig. 7 Quality of the machined surface in the machined specimen of DP1000 steel sheet of 0.8 mm thickness

Measurement results

The measurement revealed considerable differences resulting from the processes that had been used for creating the edge surfaces. The maximum force prior to cracking depended strongly on how the specimen edge had been created. For the specimen with a machined edge, the force was almost 2.5 times higher than for the sheared specimen. The first response recorded early in the graph was the specimen bending. Then, once the entire shaping punch surface had come into contact with the specimen, the force increased steeply, after which a crack initiated and began spreading from the free edge (Fig. 8 and Fig. 9).



S – sheared specimen V – water cut O – machined specimen
Fig. 8 Force dependent on piston displacement DC01



O - machined specimen S – sheared specimen
Fig. 9 Force vs. piston displacement

ARAMIS is a Digital Image Correlation (DIC) system developed to measure displacements, surface strain, velocity and accelerations of a test object. The system creates a 3D measurement and uses digital images to measure changes of the material specimen of just a few millimeters to several meters in size. The measured data is used to determine material properties of the test specimen such as Young's modulus (elastic modulus) and Forming Limit Curves (FLC).
An example of what major strain distribution prior to cracking may look like in the ARAMIS system is shown in Fig. 10.

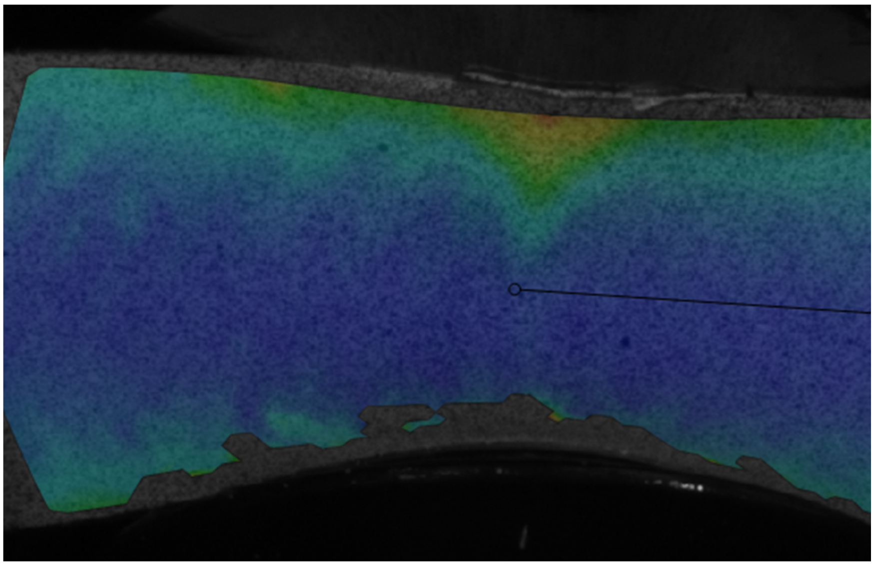


Fig. 10 The major strain from ARAMIS before a large fracture

Numerical simulation

Numerical modelling of the Diabolo test was performed using the AutoForm software. The longitudinal axis of the specimen was parallel to the rolling direction. The "roll angle" in the software was therefore set at 90°. Only a single-action draw was simulated, where the positions of the punch, the die and the blank holder are precisely defined. In this case, the specimen is held firmly by two high-strength bolts, which is why the blank holder was affixed securely. The friction value in AutoForm was set to different values in order to test which value gives results similar to the actual tests. This was done by exporting force and punch depth data and comparing it with results from the real tests in a diagram.

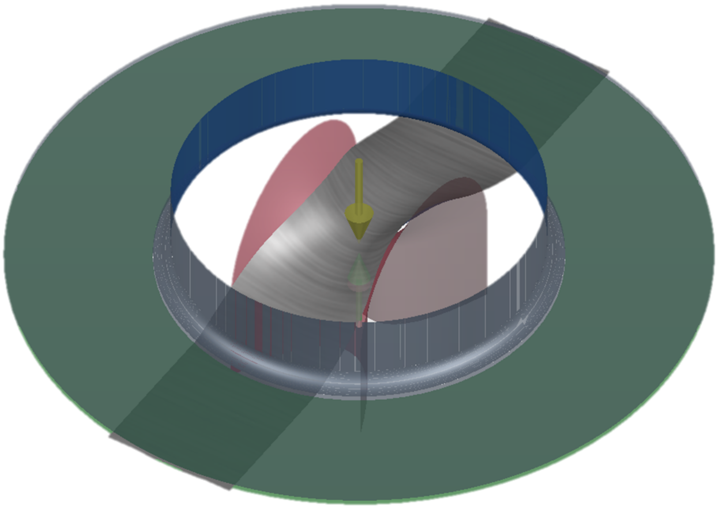


Fig. 11 An overview of the die, blank holder, punch and specimen used for the simulation

The material model embodied in the work-hardening curve has a major impact on the force magnitude computed in numerical simulation. The simulated and actually measured forces were in relatively good agreement. The damage parameters in the AutoForm software were only considered for visual evaluation of the threshold. They had no effect on the force calculation. The main goal was to adjust the damage parameters in the AutoForm software to ensure that the simulated crack forms at the same time and piston position as in the real-world test. Input values were based on the measurement and had to be defined for two manufacturing processes. The threshold strain was determined directly from the DIC ARAMIS data and then calibrated with the AutoForm software. When the threshold value is correct, red regions in the simulation identify the same critical locations for cracking at the same piston positions as in the real-world measurement. The critical region is usually associated with values near unity. This threshold value also depends on the left side of the FLC diagram which depicts the uniaxial stress state generated in the free edge and in its vicinity.

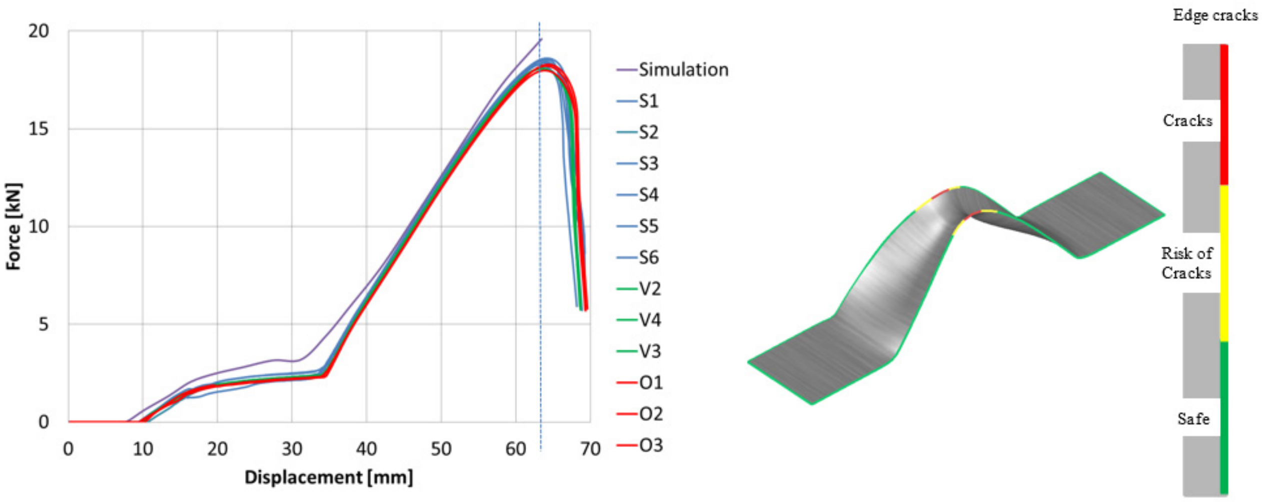
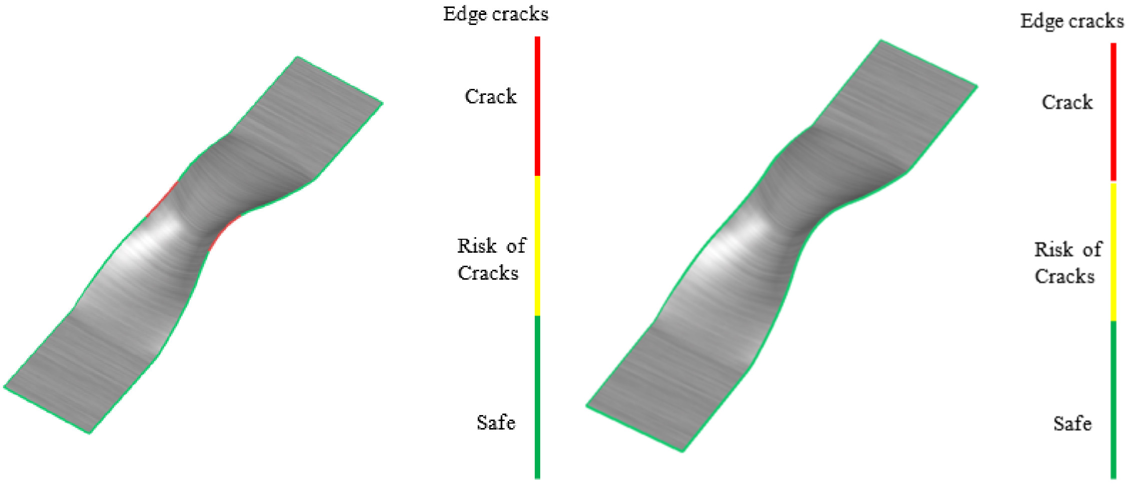


Fig. 12: a) Comparison between values from simulation in AutoForm and diabolo test b) visualization of initial crack on sample for DC01



a) Sheared specimen b) Machined specimen

Fig. 13 Evaluation of the risk of cracking by simulation for DP1000

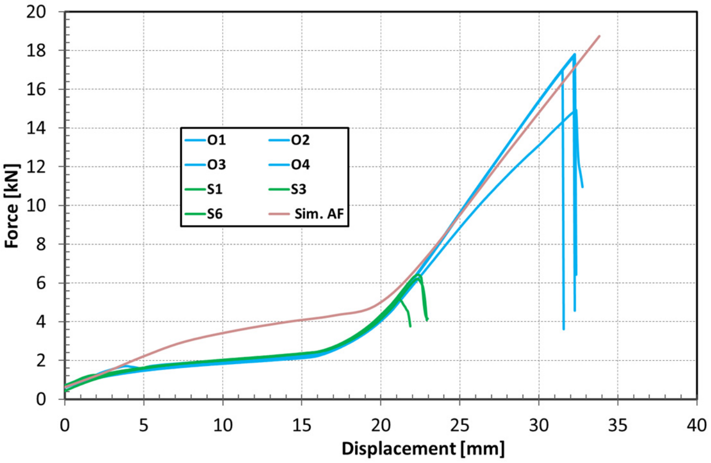


Fig. 14 Comparison between values from simulation in AutoForm and Diabolo test for DP1000

Conclusions

This paper evaluates the effects of various cutting processes on crack formation in the blank edge using the Diabolo test. The test specimens of 0.8 mm thickness were made of DP1000 steel and specimens of 1.5 mm thickness were made of DC01 steel and had two types of sheared edges. Those were produced by shearing and chip cutting. Surface roughness of these edges was measured and the microstructures in their material were examined, which revealed new aspects related to this issue. The measured strain values were fed into numerical simulation of the Diabolo test carried out using AUTOFORM software which offers the capability to use such values for modelling deep drawing processes.

Acknowledgement

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