INSTRUMENTED HOLE EXPANSION TEST

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Abstract:

Advanced vehicle concepts and light-weight design of automobiles require improved steel grades with increased strength and formability. An explicit specification of the forming properties of materials like AHS steels poses a challenge since an increase in strength is generally coupled with a decrease in material formability.

One of the methods to characterize formability of sheet materials is the hole expansion test. An instrumented hole expansion testing device was constructed in order to optimize and unify this industrially widely applied testing method. Several device parameters, such as clamping force and penetration speed were investigated. Industrially produced IF steel and Complex Phase Steel grades were selected for the trials. Specimens with standard geometry and wire cut holes were analyzed. The experimental results are compared and discussed with respect to the impact of varied device parameters.

Keywords: Hole expansion, Mechanical properties, Testing conditions, Sheet steels, Stretch flangeability

INTRODUCTION

During the last years much effort had been undertaken to improve the forming properties of sheet materials and to generalize the methods of their mechanical characterization. In the course of this development the hole expansion test has established itself since expanding machined holes during forming operations is very common in the automotive industry. During this procedure a hole is stretched to increase its diameter. Often, these flanging operations stretch material, that has already been subjected to certain plastic deformation during the hole introduction. Therefore, forming problems during the part design, as well as during the production often occur [1].

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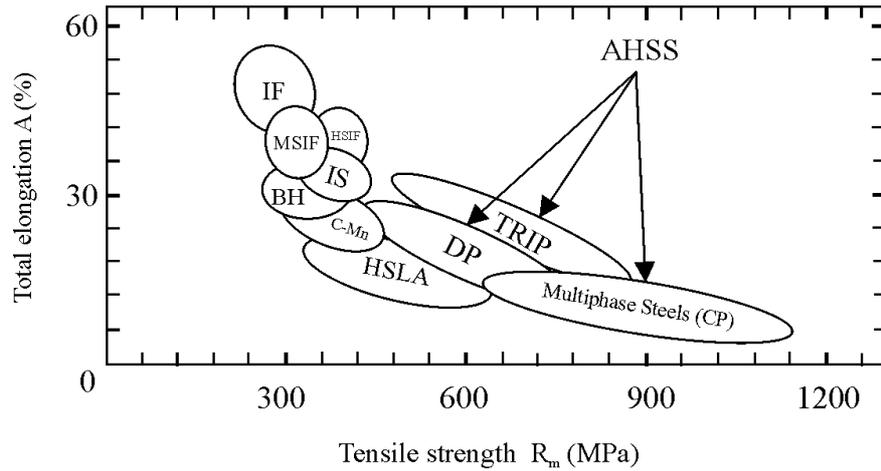
Figure 1 *Ductility–strength relationship of mild and high strength steels*

Several methods have been designed to characterize formability of sheet materials. One of the methods widely applied in industrial application is hole expansion testing. The determination of the forming limits is conducted in this case by stretching of a machined hole until failure can be observed by visual inspection, thereby evaluating the formability of the hole edge. Various approaches of hole expansion testing have been utilized [2-6]. The general purpose of the test is to determine the capacity of a material to avoid failure during the expansion of a hole. There are various factors such as material microstructure, quality of the hole edge prior to the testing, etc., which have severe influence on the results of the hole expansion test. The value to describe the capacity of a material in the hole expansion test is the hole expansion ratio.

The hole expansion ratio, λ, is calculated according to

$$\lambda[\%] = \frac{d_f - d_0}{d_0} \times 100\%, \tag{1}$$

where d_f [mm] is average hole diameter after testing and d_0 [mm] is the initial diameter of the hole.

Comstock et al. [1] investigated the influence of the edge conditions on the hole expansion ratio according to the production method of the hole. An equation is proposed to predict the hole expansion ratio for selected materials. A correlation between the hardening exponent and the hole expansion ratio for IF and austenitic-ferritic steels is shown. It is assumed that the size of the hole has no influence on the hole expansion ratio in the range of ca. 9 to 35 mm.

Karelova et al. [8] analyzed the influence of the edge conditions on the hole expansion property of dual-phase and complex-phase steels. It was found that imperfections and damage introduced into the material in the vicinity of the hole have a detrimental influence on the hole expansion property and decrease material formability.

Col et al. [9] investigated the reasons of the high achieved strains in the hole expansion test compared to the conventional tensile test. Nevertheless they regard negligible effects.

Chiriac et al. [10] investigated the influence of several parameters like the clamping force of the blank holder, the penetration speed of the cone and the alignment of the specimen on the hole expansion ratio. It is shown that the penetration speed and the clamping force do

not influence the test, but the alignment of the specimen has an observable influence on the experiment.

Although their results which are based on the hole expansion ratio are comprehensible, a more reliable method should be proposed since the hole expansion ratio is subjected to many still unexplained factors.

In order to improve the hole expansion test and to generalize the testing method, the main aim of the present work is to construct an instrumented testing device, whereby the hole expansion test can be performed at higher accuracy and control compared to the standard conditions. Main emphasis was placed on investigations outlining the influence of the device parameters on the test results, eliminating possible sources of scatter and further optimization and adjustment of the testing parameters.

TEST SETUP

The instrumented hole expansion device was realized in-house at CDL at the Technische Universität München. A special forming tool was designed for the integration into a standard tensile testing machine type W+B 600 and adapted to fulfill the ISO standard ISO/TS 16630:2003 [7]. An overview of technical specifications of the test setup is outlined in Table 1. According to the standard a surface hardness of 55 HRC for the hole expansion tool and the die is realized.

Figures 2 and 3 show the instrumented hole expansion device. Figure 4 shows a schematic illustration of the position and alignment of the punch and the specimen.
The alignment hole-punch is realized by lowering the punch before closing the clamping plate. Thereby a small preload (<100 N) is charged on the specimen. A remarkable radial penetration offset of the cone as reported by Chiriac et al. [10] did not occur.

The required clamping force claimed in the standard is 50 kN minimum. The hydraulic system is used to maintain the required clamping force, by adjusting the clamping pressure via the control unit of the tensile testing machine (max. 30 MPa).

The controlling parameter is the penetration depth, defined as the distance from the first contact of the expansion tool with the specimen surface until the stop of the punch movement. Maximum accessible penetration depth is 45 mm. The penetration force and penetration depth are recorded by the tensile testing machine, simultaneously. These parameters allow the investigation of the reliability of the setup and the influence of the clamping force and the penetration speed as reported in the next section.

Table 1 *Technical specifications of the instrumented hole expansion device*

Max. static force	600 kN
Clamping force	min. 50 kN, max. 150 kN
Clamping pressure	min. 10 MPa, max. 30 MPa
Punch diameter	62 mm
Punch length	610 mm
Punch top angle	60°
Punch surface hardness	55 HRC
Punch penetration depth	max. 45 mm
Die diameter	69 mm
Lubrication oil type	Multidraw KTL N1 (Zeller Gemelin)

Figure 2 *Instrumented HE device implemented in the tensile testing machine type W+B 600*

Figure 3 *Camera-system for the verification of the experiment*
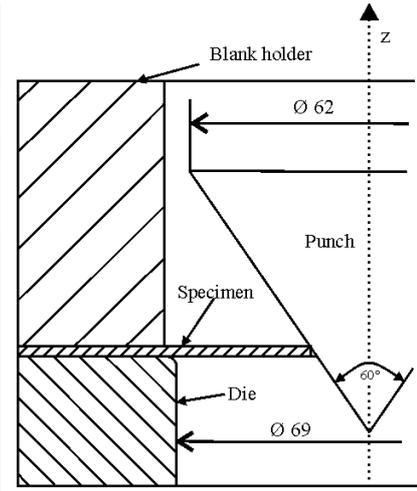
Figure 4 *Schematic illustration of the position and alignment of the punch and the specimen*

INFLUENCE OF THE CLAMPING FORCE AND THE PENETRATION SPEED

The following trials were performed with an industrially produced IF steel because high penetration depths can be achieved without cracking. The chemical composition and mechanical properties of this grade are listed in Table 2. In first tests, the effect of parameters such as penetration speed, clamping pressure on the hole expansion ratio and operational reliability were investigated. It is evident, that the measured penetration force is a result of the mechanical properties of the material, the frictional contact, the geometrical dimensions of the specimen and the expansion tool and therefore it is coherent to analyse this quantity to compare different specimens or testing conditions.

Table 2 Chemical composition and mechanical properties of IF steel used for the calibration trials

Grade	Sheet geometry [mm x mm x mm]	Chemical composition (wt.%)				$R_{p0,2}$ (MPa)	R_m (MPa)	A_g (%)	A (%)
		C	Al	Ti	Nb				
IF	1,5 x 100 x 100	0,002	0,026	0,080	0,002	165	295	25	47

The variation of the penetration force – penetration depth curves is discussed by the relative deviation in terms of the dimensionless parameter

$$V(x) = \frac{F_{reference}(x) - F_{test}(x)}{F_{reference}(x)}, \tag{2}$$

where x is the penetration depth, $F_{reference}$ is the force recorded in a reference experiment according to the standards and F_{test} is the force recorded in an experiment with changed parameters e.g. different clamping forces.

Figure 5 shows the recorded penetration force – penetration depth diagram of four tests under equal testing conditions (penetration speed 6 mm/s, clamping force 100 kN). The relative deviation (2) within this series is discussed in Fig. 6.

It is discernible that the variation of the penetration force does not exceed 30 % during the first 5 mm of penetration and after this it does not exceed 2 %. The fluctuation in the beginning of the experiment is mainly caused by imperfections in the flatness of the specimen.

Figure 7 shows the influence of the clamping force. The clamping force correlates directly to the clamping pressure via the surface of the pressure piston of the clamping tool, where 10 MPa clamping pressure is equivalent to 50 kN clamping force. No perceivable influence of the clamping force on the experiment in the investigated range can be detected. Variations up to 30 % in the beginning and 3 % during the experiment can be detected.

Furthermore Fig. 8 shows no observable influence of the penetration speed on the experiment. Merely a high scatter in the beginning may be caused by imperfections of the specimen's flatness and in the cases of 25 mm/s by impact effects. Variations, which occur at higher penetration depths do not exceed 3 % and therefore are negligible. It should be mentioned that an increased penetration speed reduces the number of recorded data points due to the fixed sampling rate of 50 Hz.

Hence, it can be concluded from the above, that the clamping force and the penetration speed do not influence significantly the penetration force – penetration depth curves in the investigated ranges, since 3 % of scatter is insignificant according to the material-specific scatter of the hole expansion tests.
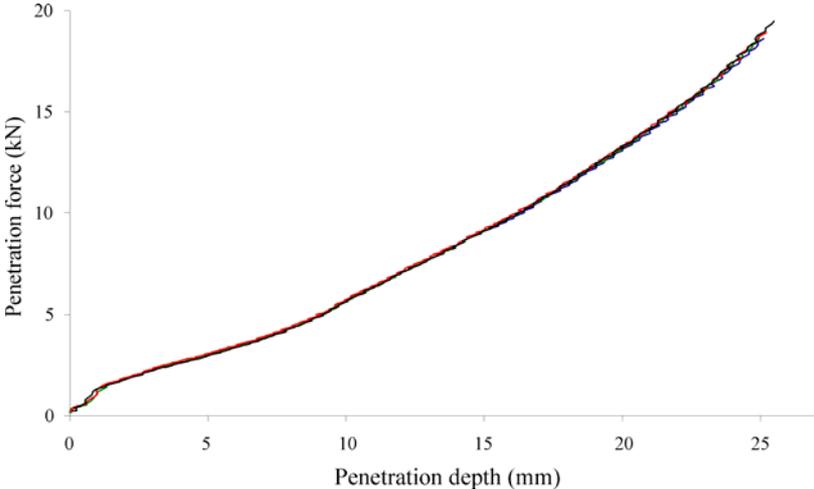
Figure 5 *Reliability. Penetration force – penetration depth diagram for IF steel. Four time repetition of the experiment with same testing conditions. Camping force 100 kN; penetration speed 6 mm/s*
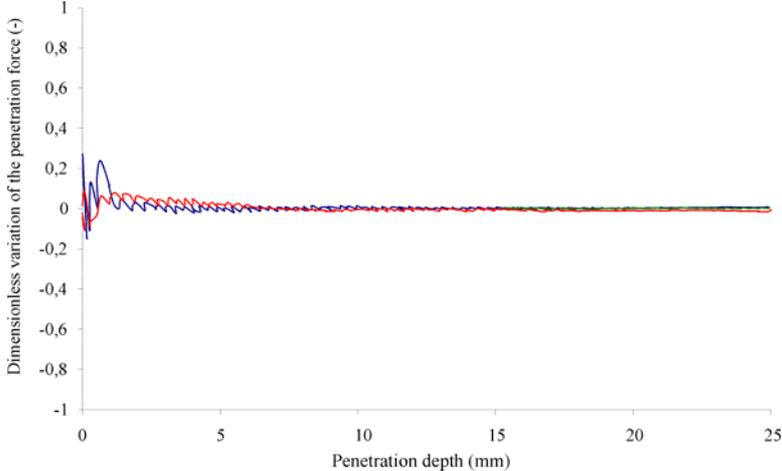
Figure 6 *Reliability. Dimensionless variation of the penetration force – penetration depth diagram for IF steel with four time repetition of the same experiment. Clamping force 100 kN; penetration speed 6 mm/s*
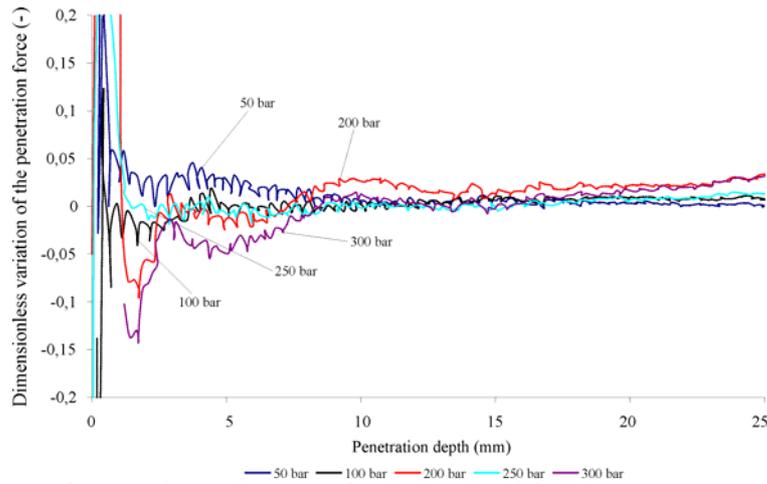
Figure 7 *Influence of clamping force. Dimensionless variation of the penetration force – penetration depth diagram for IF steel. Repetition of the experiment under changing clamping forces. Penetration speed 6 mm/s*
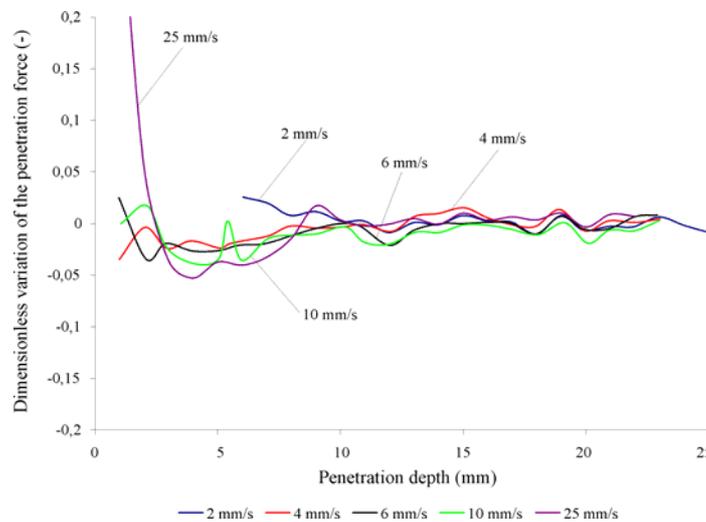
Figure 8 *Influence of penetration speed. Dimensionless variation of the penetration force – penetration depth diagram for IF steel. Repetition of the experiment under changing penetration speeds. Clamping force 100 kN*

EVALUATION PROCEDURE OF THE RECORDED PENETRATION FORCE – PENETRATION DEPTH DIAGRAMS

In contrast to conventional hole expansion testing [2-6] the hole expansion ratio is determined with the help of the penetration force – penetration depth curve. This is shown in the following using the example of testing the Complex Phase Steel CP 600, whose chemical composition and mechanical properties are listed in Table 3.

Table 3 Chemical composition and mechanical properties of CP 600

Grade	Sheet geometry [mm x mm x mm]	Chemical composition (wt.%)				$R_{p0,2}$ (MPa)	R_m (MPa)	A_g (%)	A (%)
		C	Si	Mn+Cr+M	Nb				
CP 600	1,46 x 100 x 100	0,100	0,14	~2,3	0,001	476	635	11,1	19,6

The first maximum of the recorded penetration force, the critical penetration depth, which is related to a load drop, correlates to the appearance of the first macrocrack at the hole edge, s. Fig. 10. This is proved by monitoring the hole edge by a camera system during the expansion process. Thus the two following approaches are proposed to evaluate the hole expansion ratio.

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The first method is to carry out two trials. In the first run the specimen is deformed beyond the forming limit. Then the critical penetration depth is identified by the local maximum of the recorded penetration force – penetration depth reading, s. Fig. 10. In a second run the cone penetrates the specimen until this critical penetration depth is reached. Then the specimen is taken out and the diameter of the hole is measured according to the standard. It should be noted that this specimen typically exhibits no macro cracks at the hole edge.

The second method is to conduct the hole expansion (s. Figs. 9 a, b) with an additionally installed video extensometer, whereby only one run is necessary. The reading of the video extensometer, s. Fig. 9c, can be used to determine the diameter of the hole and thus the hole expansion ratio at the critical penetration depth. Nevertheless the camera system is very sensitive to optical surface properties of the specimen requiring adequate illumination and surface preparation

The elastic springback of the specimen is neglected, since the influence of elastic springback is small (< 1 % hole expansion ratio) [11].

It should be mentioned, that the drop in the diameter – penetration depth diagram (s. Fig. 9 c) is caused by reflections of the inner surface of the hole during the clinging of the specimen to the contour of the cone. This detected diameter drop is artificial and is not indicating any damage evolution in the specimen.

| (a) View on the bottom side | (b) MINTRON camera | (c) Diameter recorded with the video extensometer |
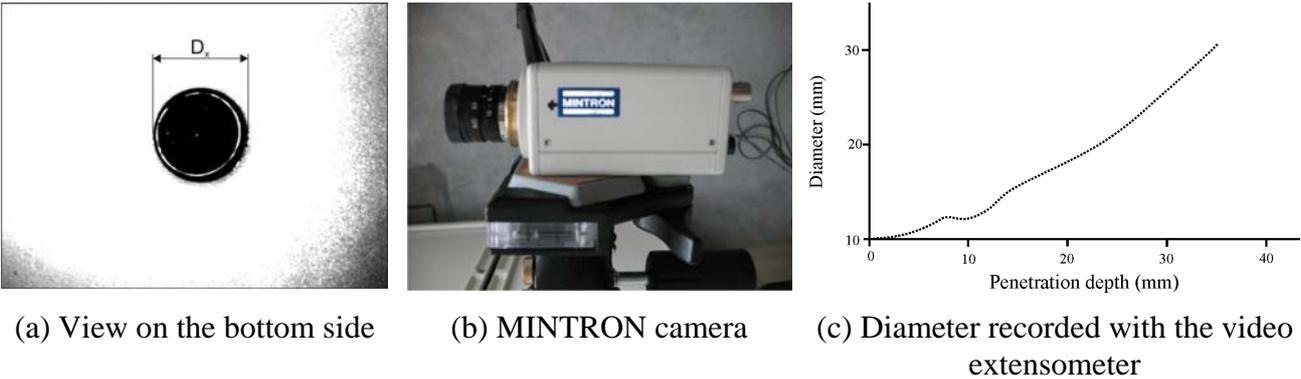
Figure 9 *Measurements with the video extensometer*
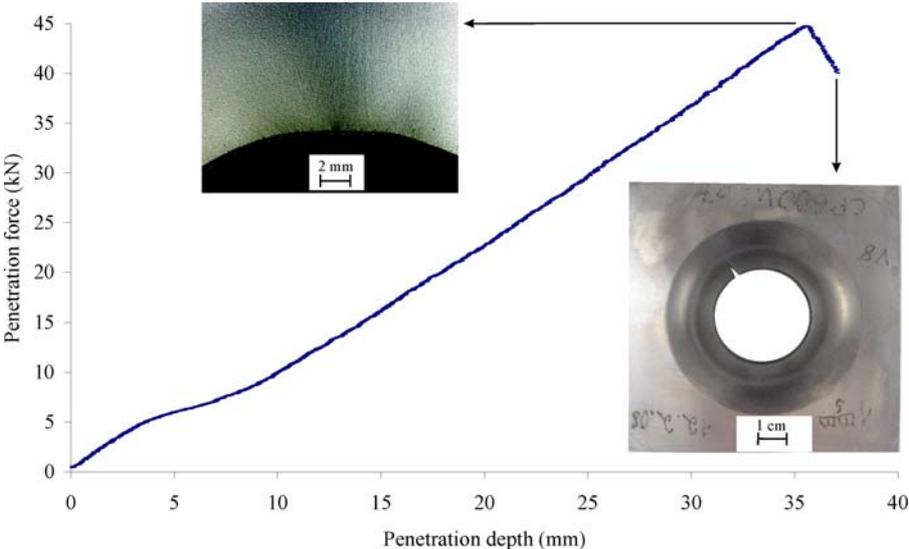
Figure 10 *Penetration force – penetration depth diagram for the complex phase steel CP600. Correlation between force drop and damage of the specimen. Clamping force 100 kN; penetration speed 6 mm/s*

SUMMARY

A special forming tool was designed and constructed to conduct the hole expansion test in a standard testing machine. Effects of the testing parameters clamping force, reliability of the machine and penetration speed on the test results were investigated.

For the examined range, it could be shown that the penetration speed, the clamping force and irregularities of the machine do not influence the experiments in a mentionable manner.

Evaluation of the penetration force-penetration depth readings with the aim to detect the crack appearance were conducted and compared with the visual observations. Force-displacement readings turned out to be reliable and valuable tools of failure detection during the hole expansion test. Investigations showed the correlation of the force drop and the deterioration of the hole edge.

Further improvements of this method are already being realized. Currently it is planned to improve the set up with additional expansion tools with different punch top angles.

References

[1]   COMSTOCK, R., J., SCHERER, D., K., ADAMCZYK, R., D. Hole expansion in a variety of sheet steels. In Journal of Materials Engineering and Performance, Vol. 15(6), December 2006, p. 675-683.

[2]   MISRA, R., D., K. THOMPSON, S.,W., HYLTON, T., A., BOUCEK. A.,J. Microstructures of hot-rolled high-strength steels with significant differences in edge formability, In *Metallurgical and Materials Transactions* A, Vol. 32A, March 2001, p. 745-760.

[3]   KARTHIK, V., COMSTOCK, R., J., HERSHBERGER, D.,L., WAGONER, R.,H., Variability of sheet formability and formability testing. Journal of Materials Processing and Technology, Vol. 121, 2002, p. 350-362.

[4]   SADAGOPAN, S., URBAN, D., *Formability characterization of a new generation of high strength steels.* Final report of AISI/DOE Technology Roadmap Program, May 2003.

[5]   HUANG, Y., M., CHIEN, K., H. Influence of the punch profile on the limitation of the formability in the hole-flanging process. In *Journal of Materials Processing and Technology,* Vol. 113, 2001, p. 720-724.

[6]   HYUN, D., I., OAK, S., M., KANG, S., S., MOON, Y., H. Estimation of hole flangeability for high strength steel plates. In *Journal of Materials Processing and Technology*, Vol. 130-131, 2002, p. 9-13.

[7]   ISO/TS 16630:2003(E), *Metallic materials – method of hole expanding test.* 2003.

[8]   KARELOVA, A., KREMPASZKY, C., WERNER, E., HEBESBERGER, T. PICHLER, A. Influence of the edge conditions on the hole expansion property of dual-phase and complex-phase steels. In *Proc. of Internat. Symposium on Advanced High Strength and Other Speciality Sheet Steel Products for the Automotive Industry*, (MS&T) 2007, Detroit, MI, USA, 2007, p. 159-169.

[9]   COL, A., JOUSSERAND, P. Mechanisms involved in the hole expansion test. International Deep Draw Research Group, IDDRG 2008 In *International Conference*, Olofström, Sweden, 2008, p. 197-205.

[10]   CHIRIAC, C., CHEN, G. *Local formability characterization of AHSS-digital camera based hole expansion test development.* International Deep Draw Research Group, IDDRG 2008 International Conference, Olofström, Sweden, 2008, p. 81-91.

[11]   DÜNCKELMEYER, M. *Characterization of the mechanical behavior of Dual Phase and Complex Phase Steels with the hole expansion test.* Diploma thesis 2008, Technische Universität München, Lehrstuhl für Werkstoffkunde und Werkstoffmechanik.