MM Science Journal | www.mmscience.eu
ISSN 1803-1269 (Print) | ISSN 1805-0476 (On-line)
Special Issue | CUTTING TOOLS 2024
1st International Conference on Cutting Tools
November 20-22, 2024, Trnava, Slovakia
DOI: 10.17973/MMSJ.2025_03_2025015

CUTTINGTOOLS2024-00006

THE EXPERIMENTAL ANALYSIS OF PLASTICITY AND FORMABILITY OF THE DUAL PHASE STEEL DP 450

J. Bilik[1], R. Sobota[1]*, J. Sugarova[1]

[1]Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology in Trnava, Institute of Production Technologies, Trnava, Slovak Republic

*Corresponding author; e-mail: robert.sobota@stuba.sk

Abstract

The choice of suitable methods for establishing of plasticity and formability of new materials has great significance for high quality formed parts manufacturing. The paper is focused on analysis of the dual phase steel DP 450 properties. This steel is used to produce selected parts in automotive industry. The properties are analysed on the base of plasticity and formability evaluation. The paper mentions results of several basic and technological tests such as static tensile tests, Erichsen cup tests, Fukui tests Schmidt cup tests and bending tests. These results are supplemented by microhardness measurements and calculations of strain hardening exponent that were based both on the Ludwik-Hollomon equation and on the strain to necking. The obtained results show that the investigated steel can be applied for forming parts not only for automotive industry.

Keywords:

Plasticity, Formability, Dual phase steel, Tensile test, Erichsen cup test

1 INTRODUCTION

Metal forming is mainly based on the ability of materials to withstand some deformations without failure. It is one of the most economic production technologies (because of the materials and energy savings), and highly productive, too. In order to utilize the advantages of forming processes, it is necessary to know the recent knowledge as well as to acquire the new one in the theory of forming and other necessary areas like metal science, etc., because of the development of new materials processed by forming. This knowledge enables sophisticated control of forming processes, improves conventional forming operations and also develops new technological operations and new methods. Very important is the choice of proper methods for establishing the plasticity and formability of new materials for formed parts production from metals or plastics or new materials for tube production [Ramkumar 2018], [Kapustova 2017].

The automotive industry has a significant share in worldwide industrial production. It significantly contributes to research and development of new materials, development of new production methods and production operations [Kucerova 2014]. One of the steel types developed and used especially in automotive industry are dual phase steels. The paper studies plasticity and formability of the DP 450 dual phase steel with focus on processing by drawing and bending. This steel is used for example for a pillar lining and a front fender production [Kvackaj 2005], [Kvackaj 2006], [Han 2015], [Wu 2011], [Spisak 2010].

2 THE INVESTIGATED MATERIAL

The material DP 450 is dual phase steel, galvanized and cold rolled with thickness s = 1.17 mm. Chemical composition of the steel and required mechanical properties are in Tab. 1 and Tab. 2.

Tab. 1: Chemical composition of the DP 450 steel [wt. %].

C	*0.05 to 0.10*	*Al*	*0.02 to 0.08*
Mn	*0.05 to 1.60*	*Nb*	*< 0.01*
Si	*< 0.40*	*Ti*	*< 0.01*
P	*< 0.04*	*V*	*< 0.01*
S	*< 0.015*	*Cr*	*< 0.80*

2.1 Microstructure and microhardness of the studied material

Optical microscopy was used for basic microstructure analysis of metallographically prepared cross cuts of samples from experimental material. NEOPHOT 30 optical microscope was used for analysis. Metallographic preparation of samples consisted of:

- Sample extraction – samples with length of approximately 15 mm were cut from various locations in test sheets.
- Mechanical grinding – by a set of metallographic papers with decreasing grain size (in order: 220, 320, 400, 600, 800 and 1200).

- Mechanical polishing - by diamond pastes with grain size of 3 μm, 2 μm and 1 μm.
- Developing of microstructure – by chemical etching in 3% Nitale, i.e. solution of HNO3 in etylalcohol.

Fig. 1 and Fig. 2 shows the microstructure of DP 450 steel with ferrite matrix and martensite.

Tab. 2: Required mechanical properties of the DP 450 steel.

Yield strength $R_{p0.2}$ [MPa]		Tensile strength R_m [MPa]		Minimum ductility A [%] 20x80	Ratio $R_{p0.2}/R_m$ [-]	Strain hardening exponent n [-]	$r_{0°}$	$r_{90°}$
Along 0°	Across 90°	Along 0°	Across 90°					
280 to 330	290 to 340	450 to 550	460 to 560	27	< 0.65	≥ 0.17	≥ 0.90	≥ 1.0

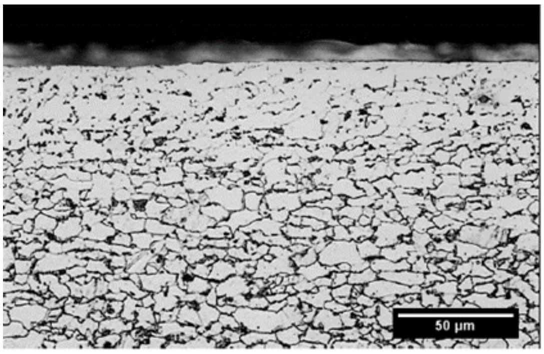

Fig. 1: Microstructure of the DP 450 steel surface layer.

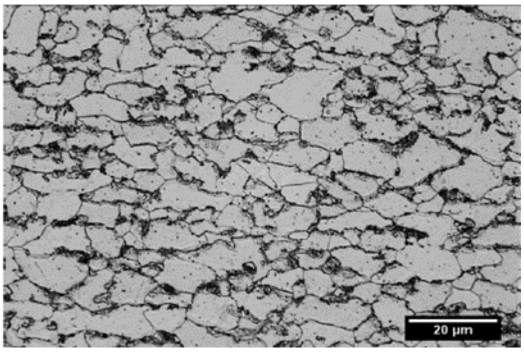

Fig. 2: Microstructure of the DP 450 steel under surface layer.

Microhardness was measured on metallograpically prepared samples with loading of 0.5 N, 10 seconds loading time, by microhardness measuring device BUEHLER INDENTAMET 1105. The results of microhardness measurement of studied material is given in Tab. 3.

Tab. 3: Results of the DP 450 steel microhardness measurement.

Microhardness HV 0.05	
Measurement 1	178.8
Measurement 2	179.9
Measurement 3	152.0
Measurement 4	174.5
Measurement 5	178.4
Average value	**172.6**

2.2 Static tensile test

The aim of tensile test was establishing the plasticity on the basis of strength and ductility characteristics [Bilik 2015]. The tensile test was executed according to STN EN ISO 6892-1 [STN EN ISO 6892-1]. The shape and dimensions of test samples used for the tensile test were shown in Fig. 3.

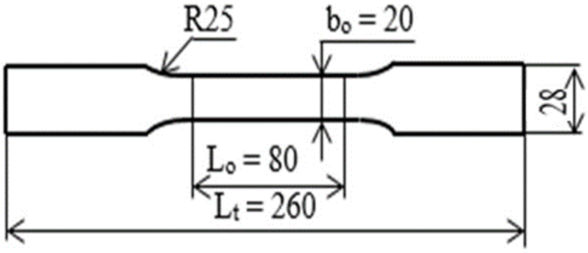

Fig. 3: Shape and dimensions of the test samples.

The results of the tensile test were in Tab. 4.

Tab. 4: Results of the tensile test for DP 450 steel.

Sample number	Strength characteristics according to standard		Real strength characteristics		Toughness characteristics according to standard		Toughness characteristics until neck creation	
	$R_{p0.2}$ [MPa]	**R_m** [MPa]	**$R_{p0.2s}$** [MPa]	**R_{ms}** [MPa]	**A_{80}** [%]	**Z** [%]	**$A_{80\ cr}$** [%]	**Z_{cr}** [%]
1	288.27	453.76	288.85	664.06	32.50	50.03	22.75	16.14
2	295.94	457.36	296.57	615.94	30.00	39.62	19.69	11.22
3	293.73	458.96	294.36	633.48	29.88	53.31	21.31	13.41
4	298.47	477.55	299.11	654.27	29.69	41.70	21.87	10.99
5	300.13	460.90	300.77	630.04	31.88	45.48	22.25	10.58
6	298.79	458.85	299.43	648.44	29.69	47.56	21.37	14.08
Average value	**295.89**	**461.23**	**296.52**	**641.04**	**30.61**	**46.28**	**21.54**	**12.74**

Plasticity index:

$$\frac{R_{p0.2}}{R_m} = \frac{295.89\,MPa}{461.23\,MPa} = 0.64 < 0.65 \rightarrow suitable \qquad (1)$$

Tab. 5 shows strain hardening exponents established based on Ludwik – Hollomon equation (first column) and on the basis of deformation until neck creation (second column).

The calculation of strain hardening exponent based on Ludwik – Hollomon equation uses the following equation:

$$n = \frac{\log R_{ms} - \log R_{p0.2}}{\log \varphi_{Rm} - \log \varphi_{Rp0.2}} \qquad (2)$$

The true (logarithmic) strain on tensile strength is determined as follows:

$$\varphi_{Rm} = \ln(1 + \epsilon_{Rm}) \qquad (3)$$

$$\varepsilon_{Rm} = A_{80kr} \qquad (4)$$

The values of R_{ms} , $R_{p0.2s}$ and A_{80kr} are presented in Table 4.

The true (logarithmic) strain on the yield strength is determined as:

$$\varphi_{Rp0,2} = \ln(1 + \varepsilon_{Rp0,2}) \qquad (5)$$

$$\varepsilon_{Rp0,2} = 0.002 \qquad (6)$$

The determination of strain hardening exponents based on deformation until neck creation (until tensile strength) is based on the equation:

$$n \cong \varphi_{Rm} \qquad (7)$$

Tab. 5: Strain hardening exponent.

Sample number	Strain hardening exponent **n** [-]	Strain hardening exponent **n** [-]
1	0.180	0.205
2	0.163	0.180
3	0.168	0.193
4	0.170	0.198
5	0.161	0.200
6	0.169	0.194
Average value	**0.169**	**0.195**

3 TECHNOLOGICAL TESTS OF MATERIAL

To analyse formability of given material the technological tests were executed in conditions close to real conditions of forming operations [Moravec 2015a], [Schrek 2016], [Schrek 2017].

3.1 Erichsen cup test STN EN ISO 20482

The aim of Erichsen cup test was an evaluation of sheet suitability for deep drawing [STN EN ISO 20482], [Kocanda 2016], [Sangkharat 2019].This test was made on Erichsen cup test device Model 102. The test sample has dimensions 90 x 420 mm. The test results were in Tab. 6

3.2 Fukui cup test

The principle of Fukui cup test is pressing of punch into a conical die (Fig. 4) until the creation of first visible crack on the test sample [Uday Kumar 2013]. The criterion of deep drawing ability for Fukui test is coefficient η_F. The test was made on three test samples with diameter D_0 = 60 mm and on three test samples with diameter D_0 = 60 mm with hole diameter d_0 = 10 mm (Fig. 5).

Tab. 6: Results of the Erichsen cup test for DP 450 steel.

Indentation number	Indentation depth until cracking h_{crit} [mm]
1	11.20
2	11.40
3	11.20
4	11.40
5	11.20
6	11.10
Average value (Index according to Erichsen IE)	**11.25**

Fig. 4: Drawing die used for the Fukui cup test.

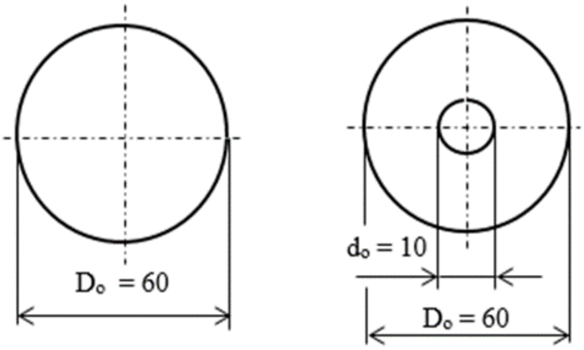

Fig. 5: Test samples for the Fukui cup test.

The results of the Fukui cup test were in Tab. 7 and Tab. 8.

Tab. 7: Results of the Fukui cup test for samples without hole.

Sample number	Diameter of the sample before test D_0 [mm]	Diameter of the sample after test D [mm]	Criterion $\eta_F = D_0/D$
1	60	46.87	1.28
2	60	47.36	1.27
3	60	48.16	1.25
Average value			**1.27**

Tab. 8: Results of the Fukui cup test for samples with hole.

Sample number	D_0 [mm]	d_0 [mm]	D [mm]	d [mm]	Criterion $\eta_F = D_0/D$
1	60	10	53.52	15.43	1.12
2	60	10	53.82	17.50	1.11
3	60	10	53.84	16.87	1.11
Average value					**1.11**

The significance of diameters in Table 7 and 8 is obvious from Fig. 5 and 6.

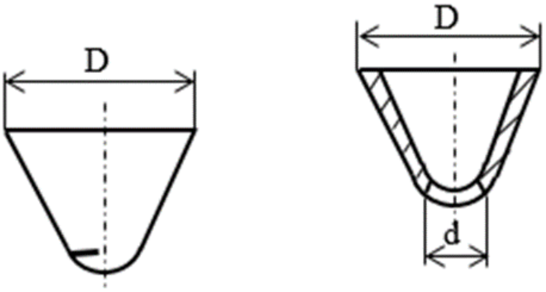

Fig. 6: Shape of test sample for the Fukui test and dimensions measured after test.

Fig. 7 shows samples without a hole and with hole after Fukui test with indicated crack creation.

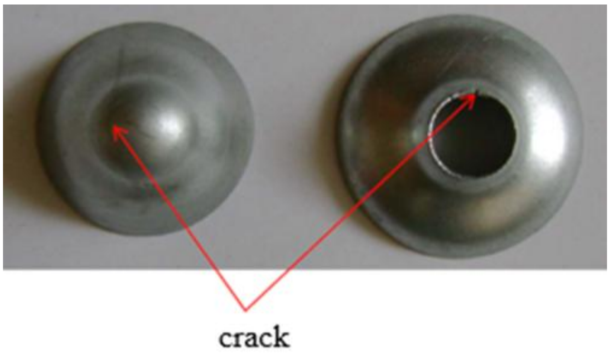

Fig. 7: Test samples for the Fukui cup test.

The cracks were created on contour line at test samples without hole so it is to conclude that the DP 450 material is suitable for deep drawing.

3.3 Schmidt cup test

The test was made to determine the limiting drawing ratio for given steel [Hrivnak 2004], [Uday Kumar 2014]. The test was made by a laboratory drawing tool with punch diameter d = 58.5 mm and with die diameter D = 61.8 mm and radius of drawing edge of punch and die was R = 6 mm. Drawing tool used for the test is in Fig. 8. The Schmidt cup test was realized on LEXN 100P eccentric press.

Fig. 8: View of a drawing tool used for determination of limiting drawing ratio according to Schmidt.

The test used blanks with diameter D_0 = 120, 121, 123, 127 and 129 mm. At blanks with diameter 120, 121, 123 and 127 mm there were no drawn parts failures during drawing i. e. the bottom is not torn off during drawing. The blank with diameter 129 mm had drawn part failure with torn off bottom (Fig. 9.).

Fig. 9: View of drawn parts after drawing test from blanks with diameters 120, 121, 123, 127 and 129 mm.

Based on test results limiting drawing ratio was determined:

$$K_{max} = \frac{D_{0max}}{d} = \frac{127}{58.5} = 2.17 \qquad (8)$$

3.4 The Güth bending test

It is used to establish minimum bend radius in tool with changing radius along its length (minimum radius is the smallest radius without crack creation in material). The test was made on the EU 40 tensile tester. The test samples had dimensions 60 x 200 mm. Fig. 10 presents a tool for Güth bending test.

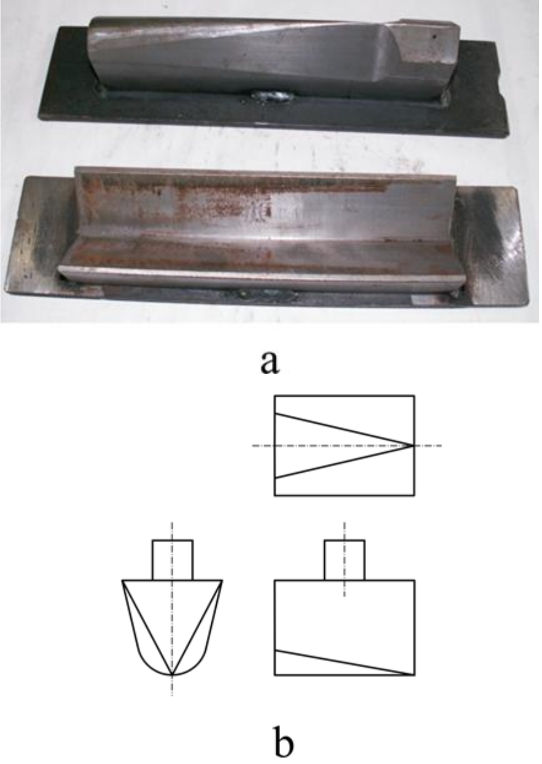

Fig. 10: Tool for the Güth bending test: a) bending tool and b) scheme of the bending punch.

The results of Güth bending test is in Tab. 9. Test sample after test is in Fig. 11.

Tab. 9: Results of the Güth bending test for DP 450 steel.

Sample number	Minimum radius on the sample ***r*** [mm]	Result
1	1.0	without failure
2	1.0	without failure

At the Güth bending test using a punch with changing radius on its length there were no cracks on the surface along the bend even on one sample (Fig. 11). The minimum bend radius on test samples is r = 1 mm.

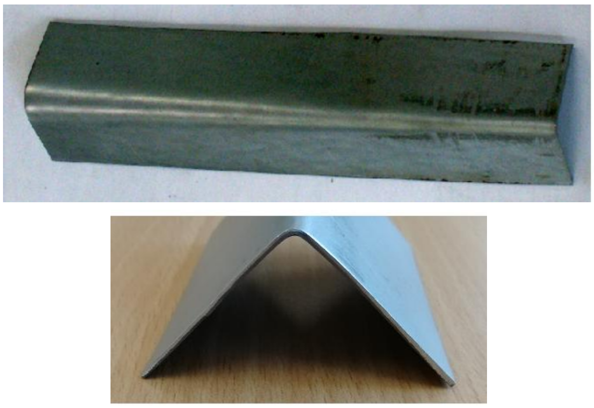

Fig. 11: Test sample without cracks after the Güth bending test.

3.5 Bending test

During the bending test the bendability of material and springback angle was studied [Hrivnak 2004], [Moravec 2015b]. Test samples with dimensions 40 x 70 mm were bent on XK 2000/2A bending machine with angle 135°25´ and bend radius R = 1 mm. The springback angle was determined by optical protractor K02. The results of bending test were in Tab. 10.

Tab. 10: Results of the bending test for DP450 steel.

Sample number	Bend angle **α** [°]	Bend angle after springback **α'** [°]	Springback angle **$\beta = \alpha - \alpha'$** [°]
1	135°25'	135°00'	0°25'
2	135°25'	134°35'	0°50'
3	135°25'	134°35'	0°50'
Springback angle average value			**0°42'**

At the bending test of DP 450 experimental material with bend angle 135º25´ and subsequently, even with angle 180°, there were no cracks on the outer bend side.

4 DISCUSSION

The microstructure of DP 450 steel consists of ferite and martensite. The ferite matrix has good plastic properties and martensite provides a higher strength of given steel. The grains are deformed and there are signs of plastic deformation in the direction of rolling. The material has a relatively small value of strain hardening exponent thus it was not significantly strengthened during plastic deformation. This can be proved by higher values of drawability (over 30 %) of given steel.

The metal materials mainly used in automotive industry are usually processed by drawing and bending. This processing creates in material some state of strain, which significantly influences the formability of a material. At chosen tests of material formability with results mentioned in tables above the final state of strain corresponds well with a state of strain created during real parts manufacturing. Therefore, the results give a real visualisation representing material behaviour at real processing conditions. As the drawing process has higher requirements on material than bending process therefore the discussion will be further focused on the problems of drawing.

The formability is influenced also by the deformation rate. Based on the Schmidt cup test parameters, the deformation rate was determined $\varphi^{\bullet} = 5\ s^{-1}$, which corresponds to the deformation rate usually used for drawing at mechanical presses. From the point of view of deformation strengthening of material during the process of forming the value of deformation is significant. For established limiting drawing ratio $K_{max} = 2.17$ the maximum value of deformation on the edge of the drawn part was $\varphi_{max} = 0.775$. Even the value of deformation on the edge of drawn part is relatively high there were no cracks because the state of strain is more favourable under blank holder at drawing as at tensile test.

For applications of formed parts where the deformation is possible like in the case of thin walled formed parts or where the corrosion resistance is important it is significant to establish residual stresses created at cold forming due to non-uniform distribution of deformations in the formed part volume.

Considering that at drawing and at bending operations there are prevalent tensile stresses on the outer side of drawn parts, the creation of residual compression stresses in the wall of drawn part can be assumed. The problem of residual stresses will be subject of further research.

5 CONCLUSION

The average value of indention depths (Erichsen index) at the Erichsen cup test was 11.25 mm. For medium drawing steel with thickness 1.17 mm the average indention depth should be more than 10.5 mm. At the Fukui test on samples without a hole, the average value of criterion was 1.27 and sheets suitable for deep drawing should have this value more than 1.2. At samples with hole the average value of the criterion was 1.11 and sheets suitable for deep drawing should have this value more than 1.1.

Based on the Schmidt cup test the limiting drawing ratio is $K_{max} = 2.17$ was determined.

From the results of the Erichsen cup test, the Fukui test and Schmidt cup test can be concluded that DP 450 steel is suitable also for deep drawing. There were no failure at Güth bending test samples even at bending radius R = 1 mm. Also, at bending test with angle 180° the test samples have not failed.

From the results of bending tests follows that studied DP 450 steel is suitable also for challenging bending operations. From obtained results can be concluded that observed DP 450 dual phase steel fulfils all requirements regarding formability and further processing by drawing and bending. Dual phase steels are widely used in automotive industry.

6 ACKNOWLEDGMENTS

The article was created with the support of the project KEGA 026STU-4/2023

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