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Evaluation of earring when drawing cups from high-strength materials

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---*ABSTRACT*---
The paper deals with the analysis of earrings during the drawing of cylindrical cups with a flat bottom from high-strength materials. The paper focuses on the comparison of the heights of cups of two high-strength steel sheets, which will be compared with the heights of cups from deep-drawn sheet metal. The cups were drawn from blanks of two diameters 63 and 66 mm with and without the use of lubricant. The evaluation methods and results from the tensile test and cupping test are presented.

Keywords *– high-strength material, uniaxial tensile test, cupping test, ears creation*

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I. INTRODUCTION

The deep drawing process transforms a flat blank into a three-dimensional hollow body. This process is widely used in many industries. The entire process is influenced by many variables, e.g. the mechanical properties of the formed material, the radius of curvature of the drawing edge of the die and bar, the shape of the blank, the coefficient of friction, etc. Incorrect setting of these parameters can lead to various errors. [1-2].

Finding the optimal values of process parameters is crucial in minimizing production costs in the deep drawing process. To determine the optimal values, it is necessary to know how the process parameters affect the deformation behavior of the sheet metal. This method of sheet metal processing is most widely used in the aerospace and automotive industries, or in the food industry in the production of cans, various packaging, etc. [2-4].

One of the undesirable phenomena in cup drawing is the formation of ears and the related earring. The earring of cups is defined as the curling of the cup at its open end. [3].

The paper evaluates the earring of the cups using a cupping test on two high-strength steel sheets, the results of which were compared with the earring during drawing of deep-drawn steel. The cups were drawn in two ways, without and with the use of a lubricant.

II. MATERIAL USED IN THE EXPERIMENTS

The paper evaluates two high-strength steel sheets, which were compared with deep-drawing steel. Microalloy galvanized steel HX420LAD (marked A) with a thickness of 0.70 mm. Double-sided hot-dip galvanized steel with transformation-induced plasticity TRIP RAK40/70 Z100MBO (marked B) with a thickness of 0.75 mm. The properties of these sheets were compared with deep-drawn steel DC06BZE75/75PHOL (marked C) and with a thickness of 0.85 mm.

III. EXPERIMENTAL METHODOLOGY

1. Uniaxial tensile test

The uniaxial tensile test was performed according to STN EN ISO 6892-1:2020, the normal anisotropy ratio according to STN EN ISO 10113:2020 and the strain hardening exponent according to STN EN ISO 10275:2021. The test was performed using the electromechanical machine TIRAtest2300. To measure the mechanical properties of the materials under study, five samples were produced and tested from each material in the directions of 0°, 45° and 90° with respect to the rolling direction.

The dimensions of the test samples for the uniaxial tensile test are shown in Fig. 1.

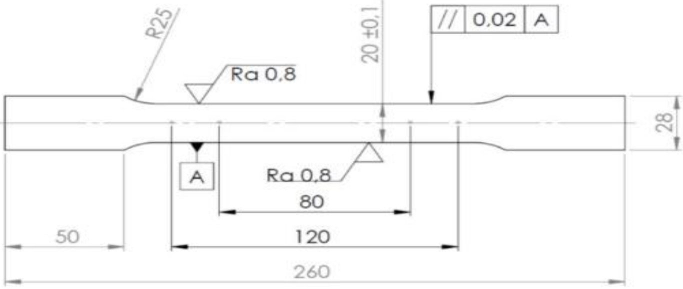

Fig. 1 Dimensions of the tested samples for the uniaxial tensile test

The average values of the mechanical properties of the tested materials obtained by uniaxial tensile testing are shown in Table 1-3.

Tab. 1 Obtained values of mechanical properties of material A using uniaxial tensile test

Dir. (°)	**$R_{p0,2}$ (MPa)**	**R_m (MPa)**	**A_{80} (MPa)**	**r (-)**	**n (-)**
0	470.5	521.5	22.2	0.790	0.143
45	465.1	511.7	24.0	1.096	0.142
90	453.5	522.0	18.8	0.599	0.151

Tab. 2 Obtained values of mechanical properties of material B using uniaxial tensile test

Dir. (°)	**$R_{p0,2}$ (MPa)**	**R_m (MPa)**	**A_{80} (MPa)**	**r (-)**	**n (-)**
0	434.8	764.9	29.6	0.702	0.298
45	442.8	763.0	29.6	0.884	0.294
90	449.0	764.0	31.0	0.867	0.279

Tab. 3 Obtained values of mechanical properties of material C using uniaxial tensile test

Dir. (°)	**$R_{p0,2}$ (MPa)**	**R_m (MPa)**	**A_{80} (%)**	**r (-)**	**n (-)**
0	156.5	300.7	46.9	2.224	0.267
45	159.0	302.3	46.0	1.552	0.256
90	148.1	298.0	49.8	1.921	0.265

Chemical analysis was performed to determine the chemical composition of the investigated materials. Table 4 shows the determined chemical composition of the investigated materials.

Tab. 4 Chemical composition of the investigated materials (%)

Material	**C**	**Mn**	**Si**	**Cr**	**P**	**S**	**Al**	**Nb**	**Ti**
A	0.05	0.71	0.26	0.05	<0.002	<0.002	0.03	0.032	<0.002
B	0.02	1.27	0.14	0.04	0.019	<0.002	2.56	0.016	0.005
C	0.002	0.06	0.02	0.02	<0.002	<0.002	0.04	0.006	0.006

2. Cupping test

The cupping test was performed using a ZD-40 hydraulic press (Fig. 2a). A special deep drawing tool was developed to evaluate the anisotropy of the cups (Fig. 2b). The drawing tool has interchangeable functional parts – a punch and a die for testing different sheet thicknesses.

Fig. 2 a) Hydraulic press ZD40, b) drawing tool

The experiment used circular blanks with diameters of 63 mm and 66 mm, from which cylindrical cups with a flat bottom were drawn during the test. 10 blanks were made for each tested material for a given diameter.

Since the thickness of the tested materials was different in the experiment, different sizes of the functional parts of the drawing tool were used when drawing flat-bottomed cylindrical cups. Table 5 shows the dimensions of the drawing tool used for blanks with a size of 63 mm and 66 mm for different types of tested materials.

Tab. 5 The dimensions of drawing tools for blank diameters of 63 mm and 66 mm

Part of the tool	**Dimensions of the tool parts (mm)**		
	A	B	C
Punch diameter	31.71	31.81	31.00
Die diameter	33.80	33.80	33.46
Rounding of the drawing edge of punch	5.00	5.00	5.00
Rounding of the drawing edge of die	5.50	5.50	5.50
Drawing clearance	2.09	1.99	2.46

The changing parameters in the evaluation of the deep-drawing properties of the investigated materials were friction and its influence on the evaluation of cup height in 8 measured directions and the earring parameter of cup ΔH.

The earring of the cups is defined as the curl of the cup at its open end. Earring represents a significant problem in the deep drawing process and is the subject of research with the aim of eliminating this deficiency as much as possible.

On each evaluated cup, the height of the ears was measured in eight places, each 45° from the previous place with a starting point of 0° with respect to the rolling direction. In this way, the values of the ear heights (mm) were gradually obtained in individual directions (H0, H45, H90, H135, H180, H225, H270, H315) with respect to the rolling direction.

The earring of the cups was evaluated by the difference between the maximum and minimum measured height (ΔH). The ΔH values were calculated from the relationship:

$$\Delta H = H_{max} - H_{min} \text{ (mm)} \quad (1),$$

where:

- ΔH - the difference between the maximum and minimum measured cup height (mm),
- H_{max} - maximum measured cup height (mm),
- H_{min} - minimum measured cup height (mm).

From the calculated value of ΔH according to (1), the arithmetic mean was calculated for each blank diameter and friction condition according to the relationship:

$$\overline{\Delta H} = \frac{\sum_{i=1}^{n} \overline{H}_i}{n} \text{ (mm)} \quad (2),$$

where:

- $\overline{\Delta H}$ − average value of the height difference for given conditions (mm),

- n - total number of selection values.

The earring cups were expressed by the ear height in the 8 measured directions and by the parameter ΔH, which was calculated according to (2).

The heights of the ear for material A with a blank diameter of 63 mm are given in Table 6.

Tab. 6 Ears heights of cups from material A for a blank diameter of 63 mm

Cup	Lubricant	H_0 (mm)	H_{45} (mm)	H_{90} (mm)	H_{135} (mm)	H_{180} (mm)	H_{225} (mm)	H_{270} (mm)	H_{315} (mm)	ΔH (mm)	$\overline{\Delta H}$ (mm)
1	without lubricant	23.45	25.41	23.25	25.73	23.53	25.02	23.43	25.24	2.48	2.35
2		23.40	25.32	23.12	25.10	24.09	25.03	23.8	24.50	2.20	
3		24.02	25.59	23.86	26.01	23.89	25.77	23.43	25.78	2.58	
4		23.88	25.08	23.71	25.54	23.55	25.23	24.00	25.50	1.99	
5		24.14	25.66	23.59	26.03	24.02	25.66	23.55	25.90	2.48	
6	with lubricant	23.67	25.57	24.07	25.87	24.01	25.77	23.59	25.33	2.28	2.31
7		23.73	25.80	23.32	25.76	23.9	25.34	24.06	25.93	2.61	
8		24.06	25.71	23.66	25.80	23.97	25.61	23.49	25.74	2.31	
9		24.07	25.44	24.20	25.52	23.92	25.81	24.12	25.39	1.89	
10		23.55	25.80	23.94	26.04	24.55	25.90	23.78	25.77	2.49	

Table 7 shows the height values for a 66 mm cutting diameter of material A.

Tab. 7 Ears heights of cups from material A for a blank diameter of 66 mm

Cup	Lubricant	H_0 (mm)	H_{45} (mm)	H_{90} (mm)	H_{135} (mm)	H_{180} (mm)	H_{225} (mm)	H_{270} (mm)	H_{315} (mm)	ΔH (mm)	$\overline{\Delta H}$ (mm)
1	without lubricant	26.73	28.55	26.80	28.65	27.07	28.53	27.01	28.83	2.10	2.33
2		26.56	28.40	26.86	28.93	26.93	28.97	26.65	28.65	2.41	
3		26.82	29.02	26.83	28.56	27.01	28.85	27.01	28.95	2.20	
4		26.57	28.73	26.57	28.78	26.22	28.42	26.75	28.39	2.56	
5		26.89	29.15	26.75	28.83	26.79	28.55	26.83	28.77	2.40	
6	with lubricant	26.94	28.65	26.85	29.00	27.55	28.71	26.75	28.76	2.25	2.43
7		26.62	28.70	26.95	28.80	27.65	29.03	27.05	29.01	2.41	
8		27.02	28.37	27.22	29.16	27.57	28.76	26.49	28.86	2.67	
9		27.12	28.22	26.76	29.23	27.08	28.74	26.88	29.22	2.47	
10		27.06	28.55	27.23	28.26	26.89	28.62	26.51	28.87	2.36	

Table 8 shows the ear heights for material B with a blank diameter of 63 mm.

Tab. 8 Ears heights of cups from material B for a blank diameter of 63 mm

Cup	Lubricant	H_0 (mm)	H_{45} (mm)	H_{90} (mm)	H_{135} (mm)	H_{180} (mm)	H_{225} (mm)	H_{270} (mm)	H_{315} (mm)	ΔH (mm)	$\overline{\Delta H}$ (mm)
1	without lubricant	25.23	26.22	25.04	26.12	25.34	26.01	25.07	26.20	1.18	1.38
2		25.68	26.30	24.93	25.59	24.7	26.10	25.07	26.26	1.60	
3		25.84	26.80	25.81	26.43	25.24	26.87	25.38	26.64	1.63	
4		25.55	26.31	25.73	26.31	25.42	26.37	25.31	26.08	1.06	
5		25.25	26.45	25.09	25.82	25.82	26.12	25.04	26.23	1.41	
6	with lubricant	25.11	26.27	25.00	25.93	25.17	25.83	24.92	2561	1.35	1.15
7		25.02	25.82	24.69	25.55	24.99	25.77	24.86	25.65	1.13	
8		24.98	25.91	25.05	25.89	24.93	25.69	25.06	25.67	0.98	
9		25.10	26.04	25.01	25.93	24.99	25.98	25.05	26.00	1.05	
10		24.80	25.53	24.92	25.78	25.11	26.03	25.02	25.85	1.23	

The values of the earring for a 66 mm blank diameter of material B are given in Table 9.

Tab. 9 Ears heights of cups from material B for a blank diameter of 66 mm

Cup	Lubricant	H_0 (mm)	H_{45} (mm)	H_{90} (mm)	H_{135} (mm)	H_{180} (mm)	H_{225} (mm)	H_{270} (mm)	H_{315} (mm)	ΔH (mm)	$\overline{\Delta H}$ (mm)
1	**without lubricant**	28.84	29.83	28.79	29.53	28.6	29.71	28.87	29.55	1.23	1.32
2		28.79	30.04	28.66	29.79	29.02	29.66	28.98	29.63	1.38	
3		29.01	29.72	28.87	29.66	28.99	30.11	28.74	29.88	1.37	
4		28.80	29.61	29.01	29.93	29.11	30.07	28.98	29.96	1.27	
5		28.86	29.73	28.94	29.77	29.00	29.55	28.87	30.19	1.33	
6	**with lubricant**	28.35	29.13	28.10	29.05	28.2	29.24	28.98	29.23	1.14	1.41
7		28.21	29.04	28.11	29.12	28.58	29.43	28.82	29.16	1.32	
8		28.01	28.83	28.07	29.01	28.21	29.44	28.76	29.56	1.55	
9		28.87	28.54	28.17	28.89	28.66	29.31	28.89	29.45	1.28	
10		28.11	28.67	28.05	29.18	28.73	29.79	29.00	29.58	1.74	

Table 10 shows the ear height for material C when drawing cups from a blank diameter of 63 mm.

Tab. 1 Ears heights of cups from material C for a blank diameter of 63 mm

Cup	Lubricant	H_0 (mm)	H_{45} (mm)	H_{90} (mm)	H_{135} (mm)	H_{180} (mm)	H_{225} (mm)	H_{270} (mm)	H_{315} (mm)	ΔH (mm)	$\overline{\Delta H}$ (mm)
1	**without lubricant**	24.87	23.34	25.09	23.21	25.35	23.11	24.95	23.36	2.24	2.34
2		25.14	23.21	24.86	22.88	24.92	23.06	24.78	23.28	2.26	
3		25.50	23.91	24.63	22.92	24.89	22.85	24.99	23.69	2.65	
4		25.20	23.22	24.83	23.00	24.55	22.94	24.83	23.12	2.26	
5		24.94	23.58	24.53	23.22	25.43	23.48	25.01	23.12	2.31	
6	**with lubricant**	23.73	22.55	24.65	22.71	24.12	22.50	24.04	22.82	2.15	2.20
7		24.64	22.89	24.37	23.26	24.09	22.71	24.11	22.77	1.93	
8		24.40	23.17	24.40	22.50	24.52	23.02	24.22	23.08	2.02	
9		24.63	22.69	24.98	22.43	25.00	22.48	24.73	22.76	2.57	
10		24.29	22.93	24.31	23.04	24.89	22.55	24.62	23.01	2.34	

Table 11 shows the ear height for a 66 mm diameter blank made of material C.

Tab. 11 Ears heights of cups from material C for a blank diameter of 66 mm

Cup	Lubricant	H_0 (mm)	H_{45} (mm)	H_{90} (mm)	H_{135} (mm)	H_{180} (mm)	H_{225} (mm)	H_{270} (mm)	H_{315} (mm)	ΔH (mm)	$\overline{\Delta H}$ (mm)
1	**without lubricant**	30.54	28.28	29.72	28.94	30.04	28.33	29.66	28.45	2.26	2.40
2		29.68	27.84	29.85	27.99	29.55	27.60	30.05	28.22	2.45	
3		29.8	27.72	30.01	27.8	30.04	27.55	29.65	27.49	2.55	
4		30.02	28.05	29.88	28.07	29.87	27.82	29.59	28.17	2.2	
5		30.07	28.11	29.98	29.63	29.93	27.55	29.83	27.87	2.52	
6	**with lubricant**	29.6	28.12	29.26	27.32	28.43	26.99	28.93	27.23	2.61	2.77
7		29.38	27.28	28.82	26.96	28.78	26.94	28.99	27.14	2.44	
8		29.18	28.12	29.26	27.32	28.43	26.64	28.77	27.07	2.62	
9		29.51	27.22	29.43	27.4	29.21	27.55	30.06	26.87	3.19	
10		29.33	27.45	29.00	27.55	29.99	27.02	29.86	27.15	2.97	

Fig. 3 shows cups from material C with a blank diameter of 66 mm.

Fig. 3 Cups from material C drawn from a blank diameter of 66 mm,
a) without the use of lubricant, b) with the use of lubricant

IV. RESULTS

The experimental part of the paper was focused on the evaluation of deep drawing of high-strength sheets, which were compared with the common low-carbon deep drawing steel DC06. The values of the earring were investigated using blanks with diameters of 63 and 66 mm. The influence of the coefficient of friction when drawing the samples was monitored by cupping test.

The average value of the height difference ($\overline{\Delta H}$) when drawing cups from material A with a diameter of 63 mm reached a value of 2.35 mm when drawing without the use of lubricant. When using a lubricant, the value of the parameter ($\overline{\Delta H}$) was equal to 2.31 mm. With a blank size of 66 mm, the earring parameter ($\overline{\Delta H}$) for material A reached a value of 2.33 mm when drawing without lubricant and a value of 2.40 mm when drawing with lubricant.

Material B showed earring parameter of 1.38 mm when drawn from a blank diameter of 63 mm without the use of lubricant. When using lubricant ($\overline{\Delta H}$) = 1.15 mm. Material B, in the case of blanks with a size of 66 mm, achieved earring parameter $\overline{\Delta H}$ of 1.32 mm when drawn without the use of lubricant and 1.41 mm when drawn with the use of lubricant.

Material C showed earring evaluated by the parameter $\overline{\Delta H}$ when drawing without lubricant with a value of 2.34 mm. When using lubricant ($\overline{\Delta H}$) is 2.20 mm. Material C with blank diameter 66 mm - in this case, the value ($\overline{\Delta H}$) reached = 2.40 mm when drawing without lubricant and 2.77 mm when drawing with lubricant.

V. CONCLUSION

High-strength steels HX420 LAD and TRIP RAK40/70 were tested and compared with deep-drawing steel DC06. Based on the results obtained from the cupping test, a significant influence of the friction coefficient when drawing cups from high-strength sheets on the values of the earring was demonstrated.

The smallest differences in cup height of all the examined sheets were shown by high-strength steel HX420 LAD at a blank diameter of 63 mm. When drawing with lubricant, the cup height was 0.04 mm lower than when drawing without lubricant.

The largest measured height difference was achieved when drawing a cup from deep-drawing steel DC06 with a blank diameter of 66 mm. The height of the cup when drawing with lubricant was 0.37 mm higher than when drawing without lubricant.

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