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The Influence of the Annealing Method on the Properties of Twice Reduced Thin Steel Sheets

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Abstract: Thin packaging steel sheet is currently used in the food industry, but it is also a frequently used material in other industries. Higher requirements for quality, reduction of energy and material intensity are the main factors that determine its development. The paper compares the test results of thin twice-reduced packaging sheets, which were produced by different annealing - continuous and batch method. Mechanical properties of these materials obtained by the uniaxial and biaxial tensile tests were compared. The anisotropic properties of thin steel sheets, which are demonstrated by the formation of ears on the cups, were evaluated by the deep-drawing cup test.

Keywords: Packaging sheet, anisotropy, uniaxial tensile test, biaxial tensile test, deep-drawing cup test

1. Introduction

The increasing use of thin packaging sheet supports its continuous development. Other significant factors that determine its development are higher requirements for quality and reduction of energy and material intensity. [1]

To improve the properties of the packaging sheet, it is necessary to know the conditions and factors that affect them. The issue of material demands is represented by reducing the thickness of the packaging sheet. Reduction in thickness is also possible by the development of innovative technologies to produce thin packaging sheets. It is a continuous casting of steel, which provides the high-quality steel with a uniform chemical composition and homogeneous structure. [3]

Twice reduced materials (DR) have recently become quite common. The second reduction takes place by cold rolling in the range of 10 ÷ 36 %. Their use is related to the transition to thinner thicknesses and higher strengths of the used tinplate sheets. Sheet thicknesses of 0.12 ÷ 0.16 mm were introduced into production. This represents a significant material saving. [5, 7]

However, it is also necessary to improve the corrosion resistance properties of the protective layers at their minimum weight (1.0/1.1 ÷ 1.4/2.0 g/m^2). Minimizing the weight of the protective layer tightens the requirements for uniformity and quality of the deposited tin coating. [1]

One of the production factors influencing their properties is the recrystallization annealing method, which is included in the production process after cold rolling to eliminate negative changes in the material. Annealing is done continuously (CA - Continuous Annealing) or by a batch method (BA - Batch Annealing). [1]

Continuous annealing

In the continuous annealing method, the annealed sheet metal strip passes through

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a system of vertical burners for 2 to 3 minutes. The heat source during annealing is the heat radiating from the ceramic tubes in which the gas flows. The annealing line consists of five chambers arranged in the direction of steel strip movement.

The thermal cycle of a continuous annealing process consists of a heating phase, a holding phase at a certain temperature and a cooling phase. By reaching an elevated temperature (for continuous annealing around 450 °C), the movement of atoms is achieved, which eliminates the dislocations formed during cold rolling and the formation of new grains, the size of which depends on the annealing conditions and temperature. This process achieves the desired sheet structure. A new method of this annealing is built-in artificial aging at temperatures around 450 °C, which allows the production of practically ageless material. [2,8]

Batch annealing

The second type of recrystallization annealing is batch annealing. The entire process, including heating, holding at certain temperature, and cooling, takes three days. Annealing takes place in batch furnaces of various shapes. The coils of sheet metal are heated in a furnace to an uneven temperature of circa 600 °C.

The recrystallization temperature must be exceeded even in the coldest part of the coil. After holding at the required temperature, cooling follows. [3] The advantage of this method is a considerable softening of the coils due to the long annealing process as well as cooling. On the contrary, the disadvantage is the time-consuming process and the uneven temperature of the annealed coils. [2]

The paper deals with the influence of annealing technology on the resulting anisotropic and mechanical properties of thin packaging sheets. The continuous and batch annealed materials produced by the second reduction were evaluated. The evaluation was performed by a uniaxial and biaxial tensile test. Continuously and batch annealed packaging sheets were also verified by a deep-drawing cup test.

In addition to the material properties, this test also considers the influence of technological conditions on the deep-drawing process. The anisotropic properties of thin packaging sheets, which are demonstrated by the formation of ears on the cups, were evaluated from the deep-drawing cup test. The results of these tests serve to optimize the test method for determining the objective properties of thin steel sheets and should create appropriate conditions for deep-drawing.

2. Evaluation of Mechanical Properties by Uniaxial Tensile Test

The uniaxial tensile test is the most commonly method used to obtain the basic mechanical properties of thin packaging sheets. The test was performed in accordance with the standard STN EN 10002-1: 2002-11 (42 0310), which prescribes the conditions and shape of the test specimen. Tinned sheets show a significant yield strength during the tensile test, and therefore the determination of the value of the maximum uniform deformation is problematic.

The significant yield strength is followed by the Lüders deformation, the magnitude of which reaches a value of 4 ÷ 10 %. On the test specimen, this is demonstrated by the fact that the deformation is caused by slip in certain sections of the specimen. It starts in one place, suddenly stops in it and moves to another place in the specimen.

For the experimental research, 4 grades of twice reduced packaging steels were selected. Two grades of materials were batch annealed (TS 550 BA and DR 550 BA, thickness 0.14 mm) and two grades of sheets were continuously annealed (TH 580 CA and DR 580 CA, thickness 0.15 mm). The designation of the samples is according to the manufacturer US Steel Košice, Ltd. (TS – Temper Soft, TH – Temper Hard, BA – Batch Annealing, CA – Continuous Annealing, DR – Double Reduced).

For the tensile test, 5 specimens were used from all examined materials in the direction of 0° and 90° with the respect to the rolling direction. The measured average values of yield strength, ultimate strength and total elongation are given in Table 1.

Based on the results of the uniaxial tensile test, the values of yield strength and ultimate strength were lower for batch annealed sheets in 0° direction with the respect to the rolling direction than in the direction perpendicular to the rolling direction. In the 0° direction, there were no structural components that would significantly strengthen the material. The failure occurred in slip planes at an angle of about 60°, which are the most suitable from the point of view of the orientation of the crystallographic lattice. There was no strengthening in this direction.

Table 1: Values of yield strength, ultimate strength and elongation obtained by tensile test.

Materials	Thickness [mm]	$R_{p0,2}$ 0° [MPa]	$R_{p0,2}$ 90° [MPa]	R_m 0° [MPa]	R_m 90° [MPa]	A_{50} 0° [%]	A_{50} 90° [%]
TS 550 BA	0.14	562.3	661.2	578.5	693.1	2.27	1.31
DR 550 BA	0.14	418.28	559.83	529.3	602.76	2.67	1.02
TH 580 CA	0.15	552.32	574.52	534.1	557.1	5.07	4.21
DR 580 CA	0.15	555.9	548.4	547.2	528.32	6.01	4.21

The yield strength values of continuously annealed sheets (TH 580 CA, DR 580 CA) were higher than the ultimate strength values in the rolling direction as well as in the direction perpendicular to the rolling direction in uniaxial tensile test. Elongation values for these materials were higher in the direction 0° than in the 90° direction with the respect to the rolling direction. Figure 1 shows an example of specimen failure after a uniaxial tensile test. All samples (from all experimental packaging sheets, differently annealed) failed without deformation spreading to the entire measured length of the test specimen. An example of a specimen failure from the experimental material DR 580 CA is shown in Figure 1.

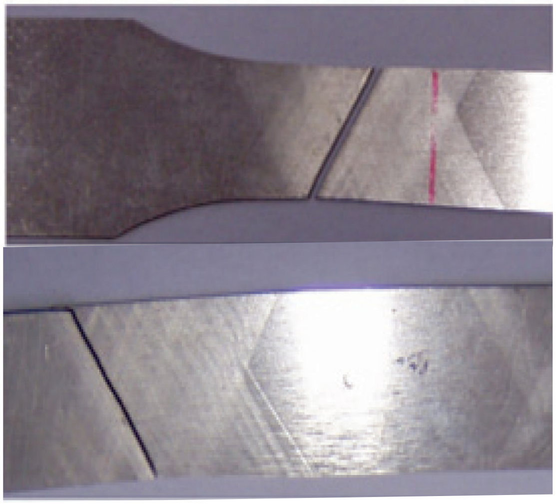

Figure 1: Specimen failure after a uniaxial tensile test.

Figure 2 shows the fracture areas of a test specimen made of experimental material DR 580 CA. The failure of the test specimen occurred by localization of the deformation of the sheet and its thinning at the point of failure (Figure 2a). Based on these facts and results in other publications [3-5], we can state that the thickness of the material influences the amount of deformation. With a smaller material thickness, the localization of deformation occurs earlier. Due to various errors (formed in the material during the production process of these packaging sheets and also during the production of samples from thin materials) the plastic deformation does not extend to the entire volume and the total deformation is smaller. Often this localization is so large that the uniform deformation does not spread further in the entire volume, but the plastic deformation stability is lost and the material breaks. Vertical view of fracture surface and Lüders deformation is shown in Figure 2b. The detail of the fracture surface clearly documents that a significant contraction occurs at the point of failure of the sample.

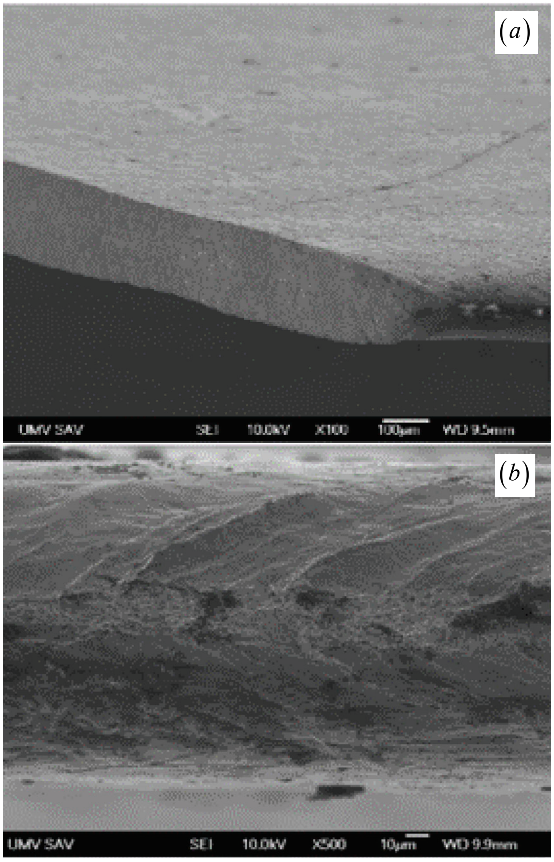

Figure 2: a) Fracture area and its detail, b) vertical view of fracture surface and slip planes .

Fig. 3a shows the imperfectly annealed structure of the batch-annealed material. The structure of hatch annealed materials should generally be characterized by "perfect" annealing of the entire volume. The advantage of batch furnaces is the restoration of the structure and significant "softening" of the annealed material due to the effect of a long annealing time and very slow cooling, during which carbon and nitrogen are completely removed from the annealed sheet in the form of stable phases. The disadvantage is the long process time and uneven temperature in the entire volume of the coil compared to continuous annealing.

Fig. 3b shows the microstructure of the continuously annealed material. During continuous annealing, partial restoration of the grains may occur due to higher deformation rates. There are hints of old grains.

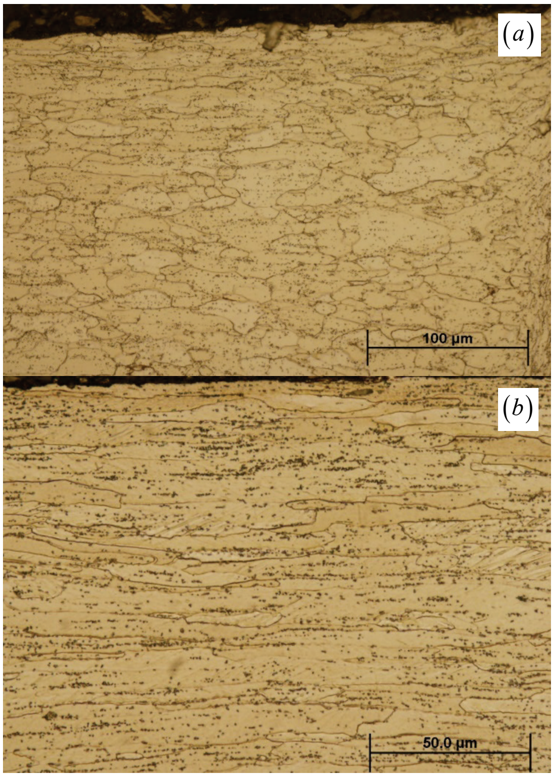

Figure 3: a) Imperfectly annealed structure of DR BA sheet, b) microstructure of DR CA sheet.

3. Evaluation of Properties by Biaxial Tensile Test

During deep drawing, the sheet is often stressed by biaxial tension. Two-axis tension is one of the most unfavorable stress patterns and therefore it is advantageous to use this method when assessing the properties of sheets [4].

The biaxial tensile test was performed on equipment available to the Department of Technology, Materials and Computer Aided Production (Figure 4a). The test is performed by bulging the tested sheet with a hydraulic fluid, which is supplied under pressure. The test specimen (130x130mm) is clamped between the bottom plate and the punch. The supplied pressure fluid bulges the test specimen to failure (Figure 4b). The criteria for the ductile properties of the tested sheet are the height of deep-drawn cup at failure of the sheet, the pressure of the supplied liquid which is sensed by the sensor, the shape of the crack after failure and the surface of the cup.

The same materials were used in the biaxial tensile test (bulge test) as in the uniaxial tensile test and the following parameters were evaluated: yield strength, ultimate strength (after failure of the specimen), height of the cup and total deformation [2].

Properties of the samples were expressed by the elongation in a biaxial test.

$$"Elongation" = \frac{l - l_0}{l_0} * 100 \qquad (1)$$

where: l_0 – sample length before failure [mm],
l – sample length after failure [mm]

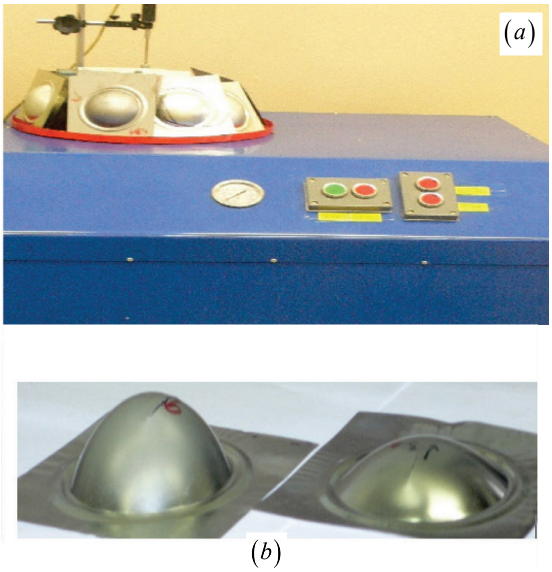

Figure 4: a) Bulge test machine, b) specimen after failure.

Table 2 shows the values obtained by the biaxial test.

Table 2: The values obtained by the biaxial test.

Material	*Thickness[mm]*	*$R_{p0,2}$(biaxial)[MPa]*	*R_m (biaxial) [MPa]*	*"elongation" (biaxial)[%]*	*h [mm]*
TS 550 BA	0.14	552.7	584.9	5.01	10.92
DR 550 BA	0.14	528.3	564.2	6.1	12.2
TH 580 CA	0.15	512.9	571.2	11.1	15.93
DR 580 CA	0.15	491.8	560.7	11.5	16.73

Comparison of uniaxial and biaxial test results

In Figures 5 ÷ 7 are compared the values of yield strength, ultimate strength and elongation obtained by uniaxial tensile test (in the 0° and 90° direction with the respect to the rolling direction) and biaxial tensile test.

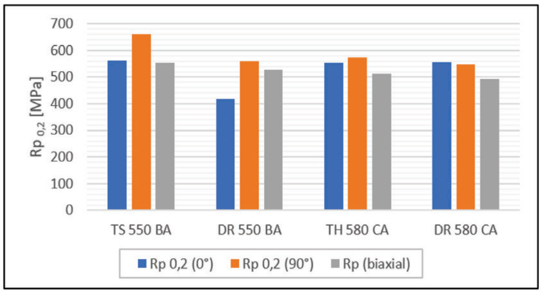

Figure 5: Comparison of yield strength values obtained by uniaxial and biaxial tensile test.

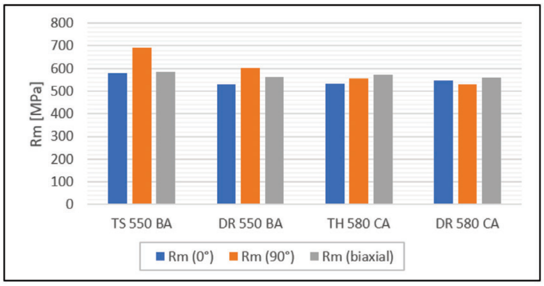

Figure 6: Comparison of ultimate strength values obtained by uniaxial and biaxial tensile test.

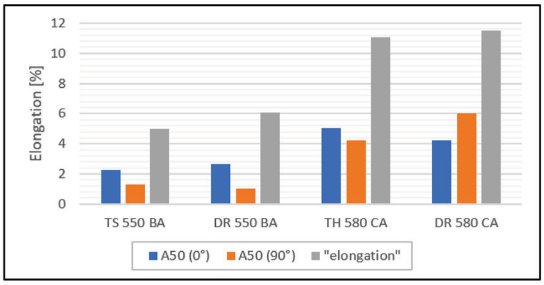

Figure 7: Comparison of elongation values obtained by uniaxial and biaxial tensile test.

Figure 5 shows that the yield strength values obtained by biaxial tensile test are lower for both CA materials and BA materials than the yield strength values obtained in the uniaxial tensile test in the 90° direction. The yield strength values obtained by biaxial tensile test for BA materials are higher than for CA materials.

Figure 6 shows that the ultimate strength values obtained by biaxial tensile are lower for BA materials than the ultimate strength values obtained in the uniaxial tensile test in the 90° direction with the respect to the rolling direction. The ultimate strength values for CA materials are higher for biaxial test in 90° direction with the respect to the rolling direction. Ultimate strength values obtained by biaxial tensile test for BA materials are higher than for CA materials.

Elongation values obtained by biaxial tensile (Figure 7) are higher for all tested materials than the values obtained by uniaxial tensile test in both directions. The elongation values obtained by biaxial tension test in CA materials are higher than in BA materials.

4. Evaluation of Anisotropy by Deep-Drawing Cup Test

Deep-drawing cup test was performed to evaluate the anisotropy of experimental materials. Diameter of circular blanks was D = 55 mm. Five test specimens were produced from each type of packaging sheet. A tool for evaluating anisotropy by a cup test is shown in Figure 8a.

The anisotropy of the sheets is manifested by the unequal cup height (Figure 8b) in different directions with the respect to the rolling direction of the sheet. In the evaluation, we used the following methods of expressing anisotropy: mean ear height Δh, ear height expressed as a percentage Z, and maximum height difference. For the earing evaluation of DR packaging sheets recommended values for a thickness of 0.14 - 0.155 mm [1] are Z < 2.5%, max. yield height difference < 0.85 mm and mean ear height 16.2 ± 0.1 mm. The calculated values after the cup test are given in Table 3.

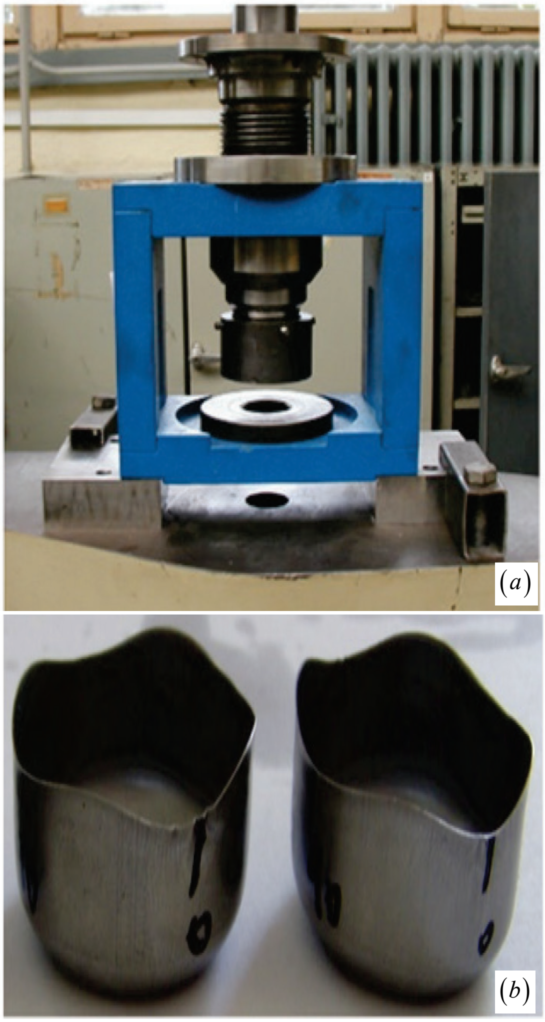

Figure 8: a) Cup test tool, b) Cups made by deep-drawing cup test.

Table 3: Measured and calculated values of the chipping coefficient, the degree of chipping and the maximum heigh difference.

	Z [%]	*Δh [mm]*	*Max. height difference [mm]*
TS 550 BA	3.38	-0.15	0.65
DR 550 BA	3.49	-0.29	0.63
TH 580 CA	3.88	-0.36	0.78
DR 580 CA	3.53	-0.49	0.8

Although elongation of the continuously annealed steel sheet samples was 2 times higher than that of the batch annealed sheet samples (Tables 1 and 2), these sheets still had low elongation values compared to the deep drawn sheets. Despite this fact, during the deep-drawing cup test, we produced cups of the stated size and shape without any problems.

Although the measured characteristics of anisotropy (Table 3) do not meet all three recommended criteria at the same time, the earing of all examined sheets is not significant. The results show that by comparing BA and CA packaging sheets, continuously annealed sheets show higher chipping. The highest chip coefficient was calculated for the specimen from TH 580 CA and the lowest for the sample from TH 550 BA. For CA sheet specimens, all three evaluated earing parameters were higher than for BA sheet specimens.

5. Conclusions

The paper evaluated twice reduced packaging sheets, which were produced by batch and continuous annealing. By comparing the results from the uniaxial and biaxial tensile test, we can say that the recrystallization annealing method influences all evaluated properties: yield strength, ultimate strength and elongation.

Batch annealed steel sheets (TS 550 BA, DR 550 BA) had different strength properties (yield strength and ultimate strength) than continuously annealed steel sheets (TH 580 CA, DR 580 CA) in both uniaxial and biaxial tensile test.

The yield strength values of continously annealed sheets (TH 580 CA, DR 580 CA) were higher than the ultimate strength values in the rolling direction as well as in the direction perpendicular to the rolling direction in uniaxial tensile test. As a result, the deformation during uniaxial tension test is localized and the sample is subsequently broken without the deformation spreading to the entire measured section.

Samples from continuously annealed steel sheets had higher elongation compared to samples from batch annealed steel sheets in both uniaxial and biaxial tensile tests. Overall, the ductility values were higher for all investigated materials under biaxial stress compared to the ductility determined by uniaxial stress.

When evaluating the achieved results from the deep-drawing cup test, it can be stated that the higher ear height expressed as a percentage Z was showed in the continuously annealed packaging sheets.

From the results we can state that the uniaxial tensile test for thin packaging sheets twice reduced does not provide relevant results, especially about its plastic properties. Despite the low elongation, there were no problems in drawing the cups during the deep-drawing cup test.

Acknowledgment

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