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The Impact of Annealing Process on the Mechanical Properties of TS550BA and TH550CA Steel Sheets

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Abstract: Packaging material is the most widely used material in the food industry, which is used to produce a variety of cans, caps, lids, and beverage containers. In this work, the effect of annealing process on the mechanical properties of thin steel sheets is evaluated. The mechanical properties and the effect of springback were investigated on two types of double reduced thin steel sheets. Batch annealed steel TS550BA and continuously annealed steel TH550CA, both steel types had a thickness of 0.18mm. Uniaxial tensile test, bulge test and springback test were used to evaluate the mechanical behavior of the selected steel plates. The bulge test was performed using our designed device. Regarding elongation values obtained from uniaxial tensile test, TH550CA steel experienced higher values (30% higher in average) in both tested directions compared to TS550BA steel. The dome height values also suggest that TH550CA steel can sustain higher plastic deformation under biaxial tension, average dome height of TH550CA was 35.4% higher. Overall, higher deformation values were obtained for TH550CA steel, both in tensile test and bulge test.

Keywords: Annealing, batch annealing, continuous annealing, tin steel sheets, mechanical properties

1. Introduction

In tin plating, a widely used industrial technique in food packaging, cold-rolled annealed steel is coated with tin, which gives it a corrosion-resistant and shiny surface. This complex process involves several steps: first, the steel sheets are cleaned with acid to remove surface contaminants such as rust, grease, or oil. Then, pure tin is electrodeposited onto the prepared surface to create a glossy appearance and the characteristic tin color, resulting in a matt finish. A heat treatment close to the melting point of tin (232 °C - 265°C) is often applied. Subsequently, during brightening, a chemical reaction between tin and iron occurs, resulting in the formation of intermetallic iron-tin compounds. The structure and orientation of the tin grains and the underlying steel together influence the final properties of the tin-coated steel. [1-3]

Tinplate is a thin, cold-rolled sheet of low-carbon steel that is coated with pure tin on both surfaces to give it a stunning metallic sheen. This material offers remarkable properties such as corrosion resistance, solderability and weldability. [4]

The main metal substrates used in packaging materials are tinplate, tinless steel, stainless steel and often aluminum. However, it is important to note that metals have the potential to interact with food, leading to corrosion and the potential release of harmful substances. [5]

To optimize material utilization, there has recently been a trend towards reducing the thickness of thin steel sheets, particularly in the case of thin packaging sheets, which requires modifications to their manufacturing processes. This reduction is

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mainly attributed to the worldwide shortage of tin resources. For many types of sheets, the thickness of the tin layer has been reduced to around 1g/m2. It is very important to note that the tin layer contributes significantly to the protection of packaging films. [6]

The material is further used in the manufacture of beverage cans, various closures, and specialized applications within the industrial packaging industry, taking advantage of its useful properties. The varied use of thin packaging materials is visually demonstrated in Figure 1. [7,8]

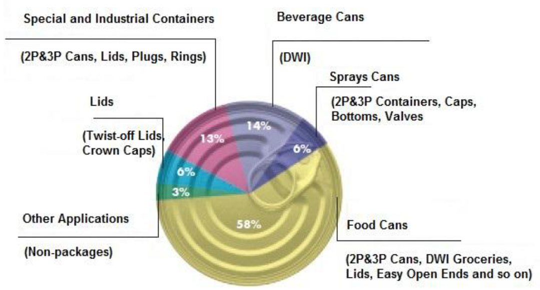

Figure 1: The varied use of thin packaging materials [7]

The recrystallization annealing method is one of the main production factors that affects the properties of thin steel sheets. It is incorporated into the manufacturing process after cold rolling to reduce adverse material changes. Annealing is carried out either by continuous annealing (CA) or batch annealing (BA).

The continuous annealing method involves passing the annealed sheet strip through a series of vertical burners for approximately 2 to 3 minutes. Heat radiates from the ceramic tubes where the gas flows and which act as a heat source. There are five chambers in the annealing process, which are aligned in the direction of movement of the steel strip. The thermal cycle in continuous annealing consists of heating, temperature maintenance and subsequent cooling phases. The elevated temperatures, typically around 450 °C in continuous annealing, facilitate the movement of atoms, remove dislocations formed during cold rolling and promote the formation of new grains. The size of the newly formed grains depends on the annealing conditions and temperature. The whole process produces the required sheet structure. An innovative aspect of this annealing method is the incorporation of artificial ageing at temperatures around 450 °C, which enables the creation of a nearly ageing-resistant material. [9-11]

The batch annealing process, which is the other type of recrystallization annealing, takes three days and includes heating, specific temperature maintenance and subsequent cooling phases. The whole process takes place in batch annealing furnaces, which have different shapes. In the furnace, the coils of sheet metal are heated to approximately 600°C to reach the recrystallisation temperature even in the coldest area of the coil. After the desired temperature has been maintained for a specified time, a cooling phase follows. The positive effect of this method lies in the significant softening of the coils because of the prolonged annealing and subsequent cooling process. However, disadvantages include long process time and unbalanced temperature distribution in the coils during annealing. [9,12]

In a previous optimization study conducted for the batch annealing process at a different integrated steel plant, Sahay et al. [13–15] developed an integrated batch annealing furnace model. This model possesses the capability to predict the spatial and temporal evolution of temperature, microstructure, and final mechanical properties of coils undergoing batch annealing. A key feature of this integrated model is its ability to directly design batch annealing cycles based on microstructure and mechanical property specifications, eliminating the need for indirect estimation through temperature differentials between hot and cold spots. This approach contributes to the reduction of coil-to-coil property variations within the plant. The effectiveness of the integrated model was demonstrated by achieving a 9% productivity enhancement in a modern batch annealing operation when compared to the prevalent thermal model. [14]

Spišák et al. [16] in their work characterized in detail the causes and consequences of loss of stability and fractures of steel packaging sheets in uniaxial and biaxial tensile loading. The analysis of deformation and loss of stability for individual tests were discussed. The analysis and observations detail the metallographic structure of material, as well as the structure and mechanism of plastic deformation. Based on the results, it can be concluded that uniaxial tensile testing does not provide objective information regarding the plastic properties of the material. The bulge test is more suitable for DR tinplate lighter than 0.18mm. It provides more objective information on the plastic properties of DR tinplate.

Mo et al. [17] investigated in their work the effect of continuous annealing temperature on the microstructure, mechanical characteristics, and texture of annealed DI plate with different temperatures (620°C, 640°C, 680°C, and 720°C). The DI plate annealed at 640 °C possesses a higher r_value and a lower |Δr| value, and its mechanical properties are the best, which will have guiding significance for the industrial production of the DI plate.

Radwanski et al. [18] studied Structure and mechanical properties of dual-phase steel following heat treatment simulations reproducing a continuous annealing line. The results were that the structure and mechanical properties of the investigated DP steel is mostly influenced by temperature and time of intercritical cooling. An increase in the cooling time and temperature leads to an increase in the martensite + bainite area fraction. This results in an increase of Rm and Rp0.2 for the case which is soaked at 810°C.

The paper deals with the impact of annealing process on the properties of thin steel sheets. The mechanical properties and springback effect were investigated on two types of double reduced thin steel sheets TS550BA and TH550CA. Uniaxial tensile test, bulge test and springback test were used to evaluate the mechanical behavior of selected steel sheets. The results obtained from uniaxial suggest that batch annealed TS550BA steel has lower values of yield (3.5%) and tensile strength (32.5%) compared to continuously annealed TH550CA steel. The dome height values also suggest that TH550CA steel can sustain higher plastic deformation under biaxial tension, average dome height of TH550CA was 35.4% higher.

2. Materials and experimental procedure

2.1 Annealing process in production of tin coated steels

During the manufacturing process in the tandem cold rolling mill, significant deformation hardening of the material occurs. This undesirable result resulting from strain hardening due to plastic deformation is reduced by continuous annealing (CA) or batch annealing (BA) (Figure 2).

2.1.1 Batch annealing

The annealing process for cold-rolled coils is influenced by factors such as steel composition, cold reduction, and the desired steel grade. Batch annealing temperatures generally fall within the range of 620°C to 690°C, slightly below the Ac1 temperature, targeting the coldest point in the charge. Cycle durations are contingent upon the desired grade and charge size, with the entire process, from heating initiation to steel removal from the furnace, potentially spanning up to one week.

Figure 3 illustrates a schematic representation

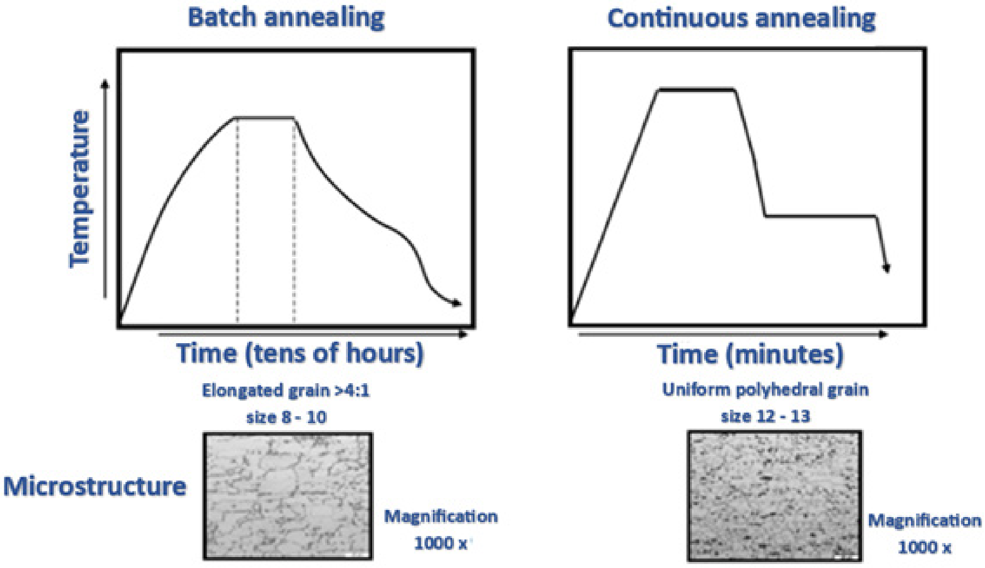

Figure 2: Batch vs. continuous annealing

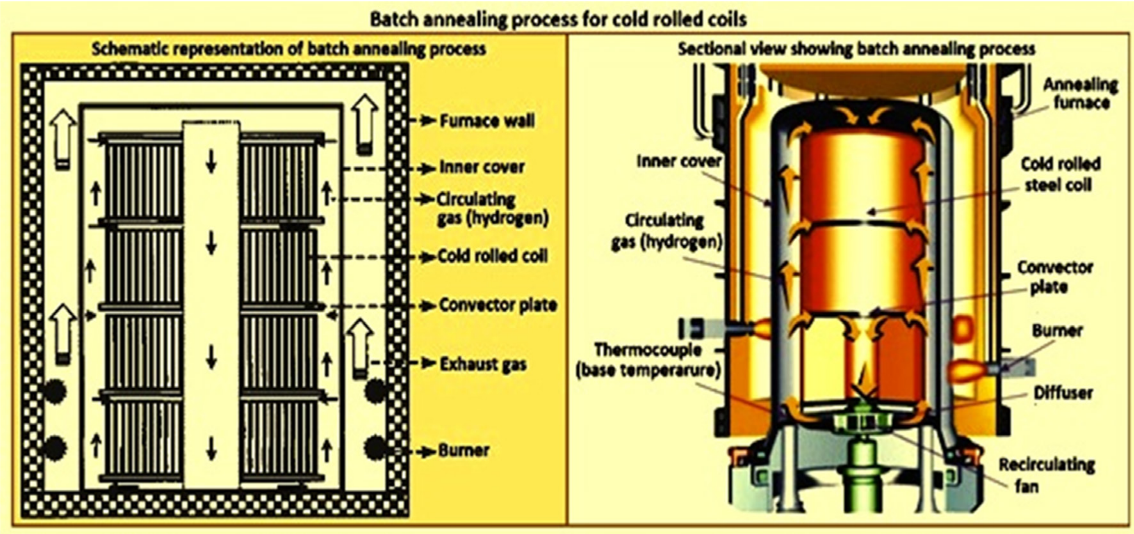

Figure 3: Batch annealing process

and a sectional view of the batch annealing process. During the batch annealing process, the recrystallization of the deformed structure initiates at temperatures of approximately 550°C through nucleation and nuclei growth. This phase utilizes the stored energy within the grains, leading to a reduction in grain density.

Prior to reaching this temperature, aluminum nitride precipitates on the sub grain boundaries affected by deformation. This precipitation hinders the nucleation of new grains, thereby retarding the recrystallization process and resulting in larger final grains. The presence of aluminum nitride is also instrumental in achieving the necessary structure for forming.

In the context of forming aluminum nitride precipitates, the coiling temperature in the hot strip mill holds significance. It should be kept low, typically around 560°C, to ensure that aluminum is in solid solution before the annealing process. While aiming for a larger grain size, a higher soak temperature is desired, yet caution must be exercised to limit it to around 730°C. Elevated temperatures beyond this threshold can lead to the formation of coarse carbides, which are detrimental to forming and can cause the sticking of adjacent layers in the coil. Figure 4 describes a typical heating and cooling cycle for batch-annealing coils of low carbon cold-rolled steel sheet. [19]

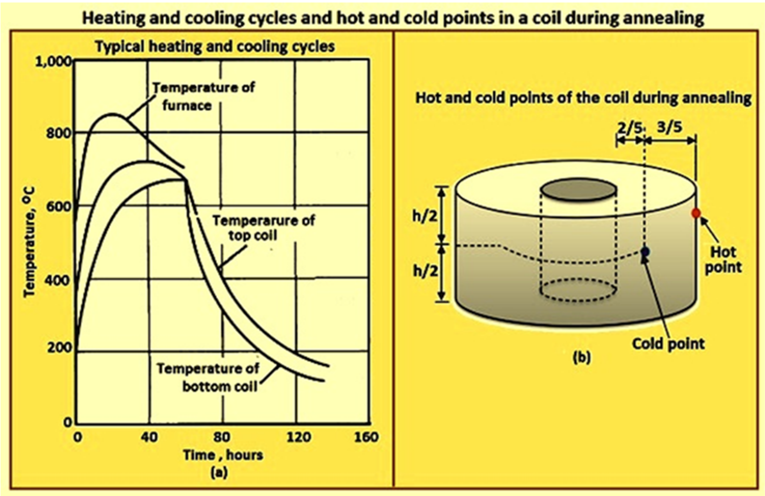

Figure 4: Heating and cooling cycles and hot and cold points in a coil during annealing

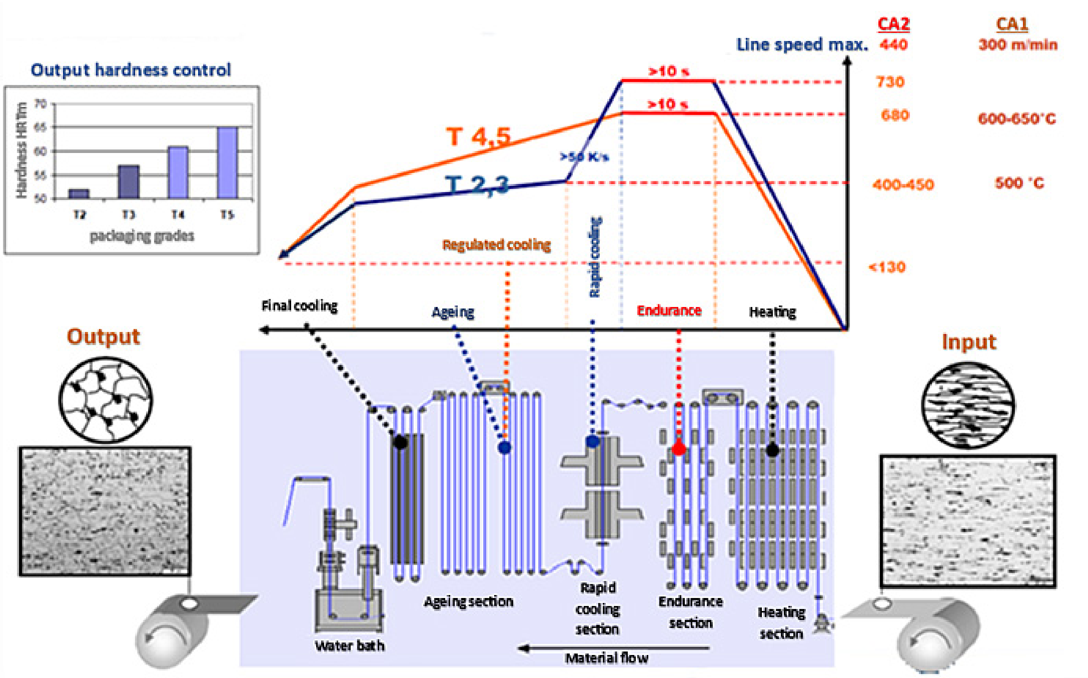

Figure 5: Schematic of continuous annealing with temperature curve

2.1.2 Continuous annealing

A schematic of the continuous annealing line is illustrated in Figure. 5, showing the temperatures and the difference in structure of the input material after cold rolling and the output material after annealing.

Continuous annealing cycles, characterized by shorter durations and higher temperatures compared to batch annealing, are employed in various applications. In certain instances, the annealing temperature may surpass the Ac1 point. Standard cycles involve 40 seconds at 700°C for cold-rolled commercial quality steel and 60 seconds at 800°C for drawing quality special killed sheet.

The majority of continuous annealing processes for cold-rolled sheets incorporate an over-aging treatment designed to precipitate carbon and nitrogen from solution in the ferrite, thereby reducing the likelihood of strain aging. Over-aging, lasting 3 to 5 minutes at temperatures ranging from 300°C to 450°C, achieves the desired precipitation of carbon and nitrogen.

While batch annealing and continuous annealing share similarities, they yield slightly different properties in annealed steel. For batch-annealed cold-rolled commercial quality plain carbon steel sheets, typical average properties include a yield strength of 210MPa and elongation of 43%. In contrast, continuous-annealed sheets exhibit properties such as a yield strength of 228MPa and elongation of 41.7%. [19]

2.2 Materials and methodology

In the experiment two types of double reduced thin steel sheets were used. Batch annealed TS550BA steel (1.0385) and continuously annealed TH550CA steel (1.0373) according to EN 10202:2022 [20], both types of steel had thickness of 0.18 mm.

Uniaxial Tensile Test

The experiment testing was conducted in the Laboratory of Testing Mechanical Properties, which is part of the Faculty of Mechanical Engineering, Technical University of Košice. In the analysis of thin steel sheets, the Ultimate Tensile Strength, Yield Strength, and ductility of the material are commonly measured. These properties are obtained from a uniaxial tensile test. To evaluate the anisotropic characteristics of the material, samples are extracted in both 0° and 90° directions relative to the rolling direction for the tensile test. The specifications of the tested sample are illustrated in Figure 6.

Mechanical properties obtained from uniaxial tensile test of the TS550BA are shown in Table 1. Properties of the TH550CA are shown in

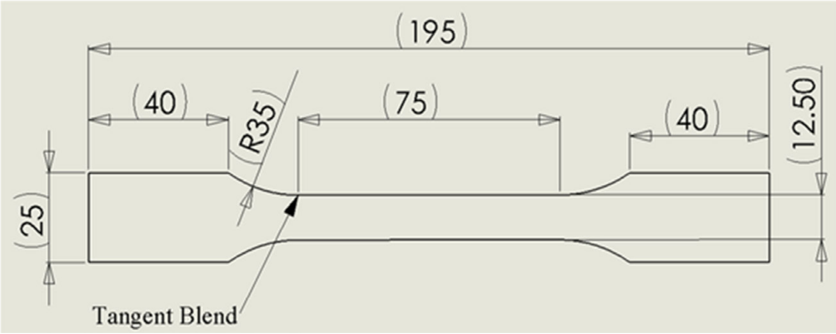

Figure 6: Technical drawing of the tested sample for the Uniaxial Tensile Test

Table 2. Testing of material properties was done according to EN ISO 6892-1:2020 [21], standards on material test machine TIRAtest 2300. This test machine is equipped with tensimeter, longitudinal extensometer and with a sensor which is used for measuring thinning of tensile test specimen during testing.

Tensile test curves for individual samples were recorded, comparison of TS550BA and TH550CA curves is shown in Figure 7.

Bulge Test

To compare the behavior of the tested steel sheets under various stress and strain conditions, a bulge test was employed in the experimental procedure. The test was conducted using our custom-designed equipment, which is depicted in Figure 8. The relevant specifications of the testing equipment are: Hydraulic pump: 25MPa Pressure sensor: 0-100bar Height sensor: incremental, range: 0-50mm, precision 0.001mm. The advantage of the designed equipment for the bulge test is the fact that a test specimen is used for the test—sheet metal with dimensions of 130mm × 130mm. The average values from this test were determined using 3 test samples of each material. The designation of samples CAB_01 (02, 03) represents material

Table 1: Mechanical properties of TS550BA

Direction [°]	*Sample Designation*	*Yield Strength R_e [MPa]*	*Tensile Strength R_m [MPa]*	*Uniform Elongation A50 [%]*	*Poisson´s Ratio V [-]*
0	BA_01	452	457	4.28	0,3
0	BA_02	432	441	4.19	0.3
0	BA_03	443	450	4.22	0.3
90	BA_901	420	429	4.52	0.3
90	BA_902	415	425	3.82	0.3
90	BA_903	426	435	4.26	0.3

Table 2: Mechanical properties of TH550CA

Direction [°]	*Sample Designation*	*Yield Strength R_e [MPa]*	*Tensile Strength R_m [MPa]*	*Uniform Elongation A50 [%]*	*Poisson´s Ratio V [-]*
0	CA_01	588	608	5.93	0,3
0	CA_02	586	606	5.74	0.3
0	CA_03	585	606	4.82	0.3
90	CA_901	572	573	5.78	0.3
90	CA_902	579	580	7.61	0.3
90	CA_903	575	577	6.06	0.3

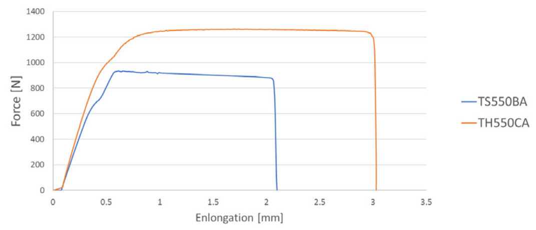

Figure 7: Tensile test curves of TH550CA and TS550BA

TH550CA, Bulge test, sample number 1(2, 3). And the designation of samples BAB_01(02, 03) represents material TS550BA, Bulge test, sample number 1(2, 3).

The bulge test involves the following procedural steps:

1. Expand the sheet metal by applying internal pressure, ensuring that the sheet's edge is securely held to prevent axial movement.

2. Continuously measure the internal pressure and bulge height throughout the expansion process.

3. Analytically convert the collected data into true stress-strain data.

4. Employ the least-squares method to fit the data into established and widely used equation forms, resulting in a flow stress curve that is easily applicable. The bulge tooling can also serve as a quality control tool.

This test, offering a rapid assessment of the formability of sheet material, proves suitable for laboratory applications, enabling the evaluation of input material quality before its release for production.

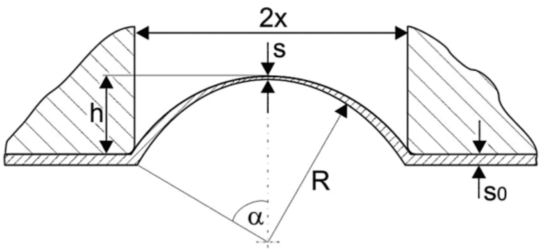

Figure 8: Geometric parameters of bulge test [22]

Springback Test

The springback test is recommended (according to some tin steel manufacturers) to evaluate yield strength of thin tinned sheets and at the same time partially characterizes its plastic properties. The sample with dimensions is used for the implementation of the test 152.4 x 25.4mm, which clamps at one end and the other free end and is bent 180° around the mandrel s with a diameter of 25.4mm using a roller. Roll up returns to the starting position and on the scale directly reads the springback angle. Three test samples of each material were used for springback test.

3. Results and Discussion

In this section, experimental results are presented and evaluated. The values of yield and tensile strength obtained from bulge test are shown in Table 3. The samples after bulge test are shown in Figure 9. For thin plates, a crack is formed in the rolling direction due to the preservation of the deformation texture after rolling.

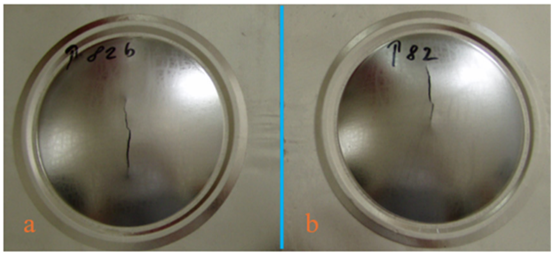

Figure 9: TH550CA samples after bulge test

Table 3: Bulge test results of TS550BA and TH550CA

Material	*Sample Designation*	*Yield Strength σ_{yB} [MPa]*	*Tensile Strength σ_{uB} [MPa]*	*Dome Height h [mm]*
TH550CA	CAB_01	529.4	610.6	18.80
TH550CA	CAB_02	519.2	614.2	18.50
TH550CA	CAB_03	515.9	608.2	19.40
TS550BA	BAB_01	549.8	621.5	13.8
TS550BA	BAB_02	560.5	622.2	14.1
TS550BA	BAB_03	555.5	621.7	14

The comparison of average values of yield strength and tensile strength from uniaxial tensile test for both materials are shown in Figure 10 and Figure 11. Experimental results of measured springback – Arm opening angle ß [°] after springback test are shown in Tab. 4. The yield and tensile strength average values obtained from uniaxial tensile test (values obtained in 0^0 direction) and bulge test were compared (Fig. 12, Fig.13).

Table 4: Springback results of TS550BA and TH550CA

Material	*Uniaxial Yield Strength Re [MPa]*	*Uniaxial Tensile Strength Rm [MPa]*	*Springback Angle ß [°]*
TH550CA	586	606	111
TS550BA	442	449	109

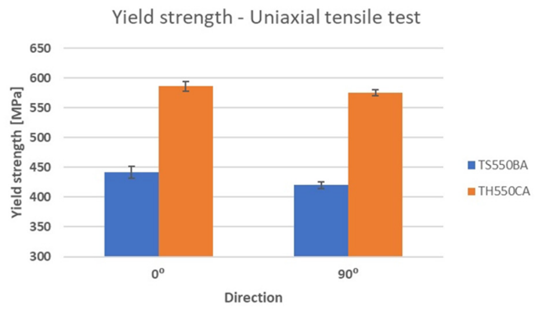

Figure 10: Comparison of average yield strength values of TS550BA and TH550CA

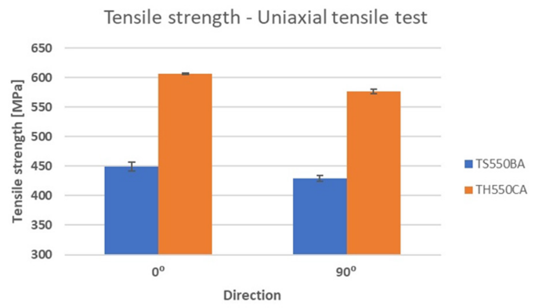

Figure 11: Comparison of average tensile strength values of TS550BA and TH550CA

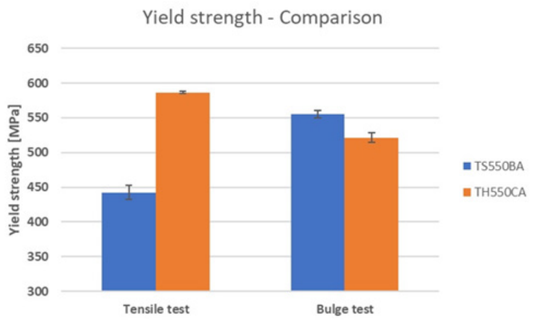

Figure 12: Comparison of average yield strength values of TS550BA and TH550CA obtained from uniaxial tensile test and bulge test

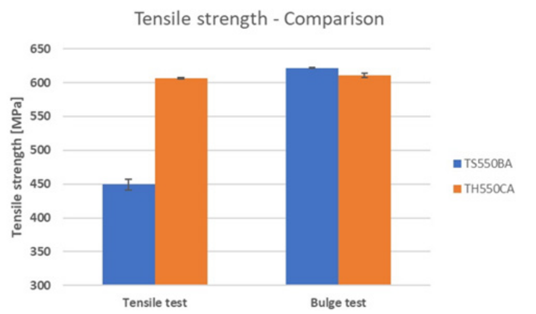

Figure 13: Comparison of average tensile strength values of TS550BA and TH550CA obtained from uniaxial tensile test and bulge test

The Springback results achieved using two different types of steel TS550BA and TH550CA suggest that yield strength has impact on the springback after plastic deformation. The springback angle of TH550CA was 2 degrees greater than of TS550BA steel.

Average yield strength of TS550BA obtained from uniaxial tensile test was 100 MPa lower compared to yield strength obtained from bulge test. In case of TH550CA steel, the average uniaxial yield strength was 30 MPa higher than biaxial yield strength.

5. Conclusions

In this study, the effect of annealing method on the mechanical properties of thin steel sheets was evaluated. The results obtained from uniaxial suggest that batch annealed TS550BA steel has lower values of yield (3.5%) and tensile strength (32.5%) compared to continuously annealed TH550CA steel. The effect of anisotropy was tested using samples cut in rolling direction (0°) and direction perpendicular to rolling (90°). In 90° direction yield and tensile strength values were lower in average for both tested materials compared to values in 0° direction. Regarding elongation values obtained from uniaxial tensile test, TH550CA steel experienced higher values (30 % higher) in both tested directions compared to TS550BA steel. Based on the tensile test results it can be stated that TH550CA is more suitable for production of packaging materials by forming, because of higher elongation values.

Results obtained from bulge test also show average lower strength (1.8%) and average yield values (6.5%) of TH550CA steel compared to TS550BA steel. The dome height values also suggest that TH550CA steel can sustain higher plastic deformation under biaxial tension, average dome height of TH550CA was 35.4 % higher. Bulge test results suggest that TH550CA is more suitable for forming operations because of higher dome height compared to TS550BA steel. Overall, higher deformation values were obtained for TH550CA steel, both in tensile test and bulge test. The values of springback suggest that TH550CA steel is more prone to springback after plastic deformation, the reason for it is higher value of yield strength compared to TS550BA steel.

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