UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS
SÁLYI ISTVÁN DOCTORAL SCHOOL OF MECHANICAL ENGINEERING

FORMABILITY INVESTIGATION OF AUTOMOTIVE THIN SHEETS

PhD dissertation's book of thesis

written by:

Gábor József Béres

Supervisors:

Prof. Dr. Miklós Tisza
Doctor of Engineering Sciences, professor

Dr. Zoltán Weltsch
PhD, associate professor

Miskolc
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1. Description and objectives of the research work

1.1 Brief description of the research topic

Recently, the energy- and material saving efforts can be clearly observed in the economy of the whole World and particularly in the developing countries. Legal regulations were also introduced in several industrial areas, such as in the automotive industry. These rules have important effect on the weight reduction of the vehicles and as a consequence the reduction of fuel consumption and the pollutant emission at the same time. This can be done in several ways, however, one of the most effective solution is the body in-white's weight reduction, namely with the less amount of applied material in the vehicle's structure. On one hand, it results in the appearance and the continuous development of advanced, high strength materials; their mechanical properties are significantly different from the previously used sheet metals. (This is mainly due to their mixed and complex, multiphase microstructure.) On the other hand, since most of the body-in-white elements (vehicle chassis elements, beams, frames, floor tiles, etc.) are primarily processed by sheet metal forming, the thorough knowledge of the sheet reaction caused by the external loads - as the formability characteristic of the materials - is definitely necessary.

During my PhD research work, I have performed experimental investigations as well as theoretical examinations on the formability behavior of three types of dual phase (DP) steels - from the family of the advanced high strength steels - and of a cold rolled, mild steel quality (DC04). These studies were supplemented in some cases by numerical simulations, too. The results primarily focus on the deformation (hardening) and the failure modes (localized necking and wrinkling) of thin sheets, or more precisely on the evaluation methods of them. However, the springback, as geometrical defect, was also thoroughly analyzed. In the following, the most relevant parts of such phenomenon will be briefly presented.

Weight-loss developments in the vehicle industry resulted relevant research results materials sciences, too. To reducing weight, newly developed, advanced high strength steels (AHSS) and ultra-high strength steels (UHSS) have been used as car body elements. Earlier [1] and present-day results [2] showed that using these steels allows thinner components for lightweight constructions with the same, or even with improved stiffness and crashworthiness. Besides, significant reduction of fuel consumption and greenhouse gas emission can be also available in this way. Dual phase (DP) steels are typically multi-phase steels belonging to AHSS's family. They are widely used in the automotive industry due to their favourable high strength and good formability. The application of these multi-phase steels for car body panels production exceeded 50% according to the European ULSAB-AVC (Ultra Light Steel Auto Body – Advanced Vehicle Concept) consortium in 2011 [3]. Therefore, studying the plasticity behaviour of these steels is still an actual topic in the metal forming society.

The plasticity (formability) properties are generally defined by the hardening and the flow rule, supplemented with the failure criteria. The hardening rule is expressed by the flow curve, which is therefore an important parameter of the deforming metal. Current FE codes contain more types of integrated equations in which the accuracy of each parameter are generally depending on the approximation method of the measured stress-strain values. The mechanical approximation models used in the dissertation are originated from Nádai [4], Ludwik [5], Swift [5], Voce [6], as well as Hockett and Sherby [7]. These researchers elaborated their equations according to different mathematical concepts, due to the complexity of the deformation process of metals. Nevertheless, this complexity is the reason why the understanding of exact processes that happen in the microstructure during plastic deformation is still timely topic of metallic materials.

In the field of the failure, the manufacturing processes in the press shop can lead to numbers of different material and geometrical defects. The most common types of practical failure modes consist of splitting, necking, wrinkling, springback and surface defects [8].

Due to the importance of the local necking, many researchers dealt with the forming limit diagrams (FLDs) of sheet metals since the 50s. Keeler gave the basis of the forming limit diagram in the 60s [9], with the investigation of major and minor principal surface strains on a blank; a limit strain graph was plotted in biaxial stretching, i.e. from plane strain tension ($\varepsilon_2=0$) up to equi-biaxial tension ($\varepsilon_2=\varepsilon_1$). Referring to the negative strain ratio, Goodwin published a paper in 1968 [10]. As a result of the physical occurrence of a local necking in the sheet, several researchers determined the failure strain under different loading conditions, but only a few studies dealt with the stress-base criteria. Stoughton and Zhu [11] published the fundamental theory of the stress-based concept, while Levy and Tyne [12] already proposed a new method for the same purpose, but from tensile properties.

From the point of view of wrinkling, the most critical region of a stamped or drawn work piece, is its flange. It is compressed by the membrane stresses in tangential direction ($-\sigma_2$), due to the radial drawing (σ_1) of the punch. Due to the complicated stress state, wrinkling can occur at the flange depending on the geometrical conditions, the applied stress state and the material properties. Generally, two widely applied solutions for wrinkling estimation can be found in the literature. One is the energy-based method [13], which interprets the occurrence of wrinkling as a compress instability condition. The other technique is the so-called bifurcation method [14] that applies a family of differential equations to get solutions. Both analytical solutions consider the restraining energy of the blank holder as the lateral surface deflection of the flange, thus neither theories create direct relationship between the applied binder spring stiffness and the drawing process. Wang and Cao [15] developed a solution for making this relationship, with analyzing the difference between the strain energy of a perfectly flat sheet and a buckled sheet.

Bending an initially flat blank along a straight line seems to be perhaps the least complicated sheet metal forming procedure. Although, the strain state is varying both in time and in space, even in the simplest cases. In some comprehensive books on sheet metal forming (e.g. Marciniak, Duncan and Hu [16], Kurt Lange [17], Altan and Tekkaya [18]), the main influencing factors of springback are specified as the flow stress (σ_f), the elastic moduli (E), the bending radii (r) and the sheet thickness (t), in the function of the bent angle (α). The growth of the strength and the bending radii increase the angle changes, but the sheet thickness reverses it. Addition, Vorkov et al [19] proposed a regression parameter fitting on known expressions and Gedeon [20] recommended another curve fit regression polynomial equation for springback evaluation.

1.2 Objectives

Since advanced materials are under continuous development, studying the correlation between the microstructure and the mechanical as well as plasticity properties was one of my basic objective. It is still a well-researched field due to the possibility of more and more advanced material characterization, but different (contradictory) results can be found in the literature. Moreover, these results were imagined as a presumably suitable basement for further purposes related to the hardening and failure behavior monitoring.

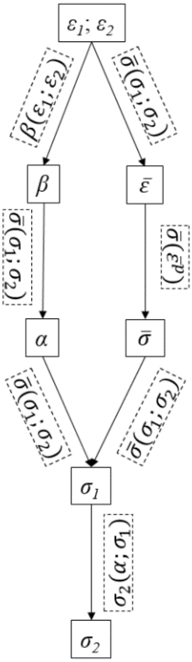

Fig. 1: Schematic view of the strain-stress transformation with the plasticity functions

Actually, the hardening or flow curve parameterization means an important part of material characterization. The known mechanical models are (at least partially) linked to the ongoing processes in the microstructure during forming. That is the reason why the research of the flow curve parameters was considered necessary by myself, too. I looked for how the mechanical model parameters' change can be linked to the microstructure distortion in such a multiphase steels.

In addition, the failure criterion is another cardinal specific of the sheet materials. These (and other) materials' behavior is less investigated in the novelty forming limit concepts, like the stress-based theories. In this approach, the known (measured or calculated) limit strains are transformed into the stress space to avoid some deficiency of the classic FLC. Ergo, the result of the transformation is explicit function of the yield criterion and the hardening curve (Fig. 1), but also the function of the strain-stress transformation methodology, in the same time.

The yield and hardening function's dependence are more or less known for the general method [11], but it cannot be said to some other methods. For example, Levy and Tyne [12] gave the limit stresses with only using the Nádai hardening and the Hill48 yield equations in their material-dependent parametric approximation. In their proposal, the limit strains are given by the sheet thickness (t) and the Z parameter.

$$FLC_0\,(\sigma) = a_0 + a_1 Z + a_2 t \quad , \qquad (1)$$

where a_0, a_1 and a_2 are material parameters.

Moreover, the different transformation methods' comparison is also missing in the literature. Thus the investigation of the forming limits in the stress-based environment was also one of my research goals.

Likewise, the stress-based evaluation possibility provided the reason for investigating the wrinkling limit of clamped surfaces. It is known that the flange of a drawn part goes through intense negative plastic deformation, so the wrinkling potential could not be approached only with taking into consideration the strain state. It also means that the wrinkling limit need to be the direct function of the normal pressure, however, it does not appear in the recent limit representation methodologies. I tried to achieve a new wrinkling criterion illustration manner, which directly contains the effect of the blank holder pressure as well. The theory, which is the basis of the new limit curves are originated from Wang and Cao [15] who deduced the wrinkling limit from the strain energy members of the flat (J_{0n}) and the buckled (J_{bn}) sheet during lateral and normal compression:

$$W_n = J_{0_n} - J_{b_n} \quad . \qquad (2)$$

Finally, the last common practical failure mode, the springback's research was also one of my objectives. To investigate the effect of the material's strength on the elastic unloading, my assumption was the monitoring of a non-conventional blank type, the laser beam welded blanks' reaction on springback.

2. Experimental investigations and applied measurement methods

2.1 Microscopic measurements

For the microstructure analysis and the calculation of the phase dispersions of DP steels, small pieces were grinded and polished by using standard metallographic sample preparation techniques and then etched in 2% nital. The calculation of the area ratios in percent of each phases were performed by the using Zeiss Imager M2m optical microscope and its program wizard software, in at least five different cross sections.

2.2 Flow curve and anisotropy determination

The engineering stress vs engineering strain curves were determined by tensile tests on Instron 4482 test machine, according to MSZ EN ISO 6892-1:2010, with 30 mm/min frame rate at room temperature. The tensile specimens had 80 mm gauge length, 20 mm width and 1mm thickness. Three directions were investigated:

parallel, perpendicular and 45° to the rolling direction. The measurements in all different specimen conditions were repeated five times. For the strain measuring, I used a contact proof Instron 2663 AVE video extensometer both in the tensile and in the transverse direction. The r-value, which expresses the anisotropy constant was defined based on the ISO 10113:2006 European standard.

The parameter fitting of each flow curve model equations were performed by the least squares' method, using the differences of the estimated ($\check{y}_i$) and the measured values (y_i) of the stress-strain function. The object was minimizing of the sum of the squared errors (χ^2), which is the square of the differences between the measured and the calculated values (3)

$$\chi^2 = \sum(\check{y}_i - y_i)^2 \quad . \tag{3}$$

The parameters were changed in all iteration steps in the solver program, until the available minimization. The estimation accuracy was defined by the quadratic regression (4):

$$R^2 = \frac{SST - \chi^2}{SST} \quad , \tag{4}$$

where

$$SST = \sum(y_i - \bar{y})^2 \quad . \tag{5}$$

2.3 Investigations for determining necking criteria

At stretch forming investigations, five different geometries embodied the minimum necessary numbers of samples to cover the FLCs from pure shear up to equi-biaxial tension. I prepared rectangular grids on the sheet surfaces to determine the major (ε_1) and minor (ε_2) logarithmic strains belonging to the onset of local necking. Vialux Autogrid® optical strain measurement system in accordance with the ISO 12004-2:2008 was used for strain measurements. An Erichsen 142 type universal sheet formability tester equipment was applied to deform the prepared samples, with poor oil lubricant. The stroke speed of the punch was 30 mm/min. The machine automatically stopped itself at the load drop caused by the occurrence of crack.

2.4 Investigations for determining the wrinkling criteria

To monitor the wrinkling of the clamped surfaces, deep-drawing experiments, more precisely standard Swift-tests [21] were performed on each material by a flat punch. The Erichsen 142 electro-hydraulic sheet metal testing equipment was used to operate the punch and the blank holder. Former one moved with constant 30 mm/min speed while latter one operated with different clamping forces. Three parallel deep-drawing tests were performed with ~0.01 g/cm^2 BWS type oil lubricant together with 0.05 mm thick polyethylene foil. These layers ensured the sandwich lubricant conditions at the die side of the blanks uniformly. The punch side remained untreated, as suggested by Altan and Tekkaya [18]. The quantitative characterization of the wrinkles was performed by Mitutoyo RA-1500 round tester machine. The harmonic analysis was filtered between 15 and 1500 µm.

2.5 Bending and springback investigations

The experimental bending tests on the raw materials were carried out by four different punch corner radius geometries (3, 5, 8 and 15 mm) and by a constant rectangular V die. The force and the displacement were monitored in real time by the Instron 4482 machine during the bending process. The forming was continued until the straight parts of the blank reached the die walls, i.e. until 90°. All samples were exposed to 10kN ironing, independently from the material grade. The springback was measured by a workshop angle meter after unloading, with ± 0.5° deviation in usual. The springback measurement technique was the same at the bending tests of the tailor welded blanks (TWBs) also, but the loading was carried out by an Amada CNC bending machine with 20 mm/min constant speed. The welded blank manufacturing was performed by laser beam welding in the BAY Zoltán Non-Profit Research Center of Applied Sciences, using uniformly 1-1 mm thick sheets from all the four investigated materials. The welding parameters are discussed in [XVI].

3. Summary of the results of the dissertation

The detailed results and discussions for all the four investigated materials can be found in the dissertation. Thereby, the main results shown here are limited to only one type of DP steel occasionally and/or to the DC04 cold rolled steel, per sub-chapters.

3.1 Basic material properties

The investigation of the basic material properties is intended to present the experimental results of the effect of the microstructure parameters on the uniaxial stress state formability. This stress state means the basis of more complex forming behaviour and this knowledge is essential for draw further consequences. Besides, measuring the tensile strength and the associated deformation is easier than that of the microstructure properties and provides sufficiently accurate benchmark for industrial users. It is also important to note that different findings can be seen in the literature for the relationship of the martensite content and the mechanical properties. These are the reasons why the microstructure and the tensile behaviour was coupled for the DP steels, in this environment.

As a result of my research work, linear correlation was determined between the martensite volume fraction (MVF) and the yield- and ultimate tensile stress (Fig. 2). Though it is not necessary self-evident base on the literature review (some literatures present non-uniform correlation between the strength and the MVF, especially for martensite contents higher than 50%), it is consistent with the former results of the Széchenyi University Győr (SZE). The approximate equations already take into consideration the SZE's results also, thus six points are indicated in the figures in this sub-chapter.

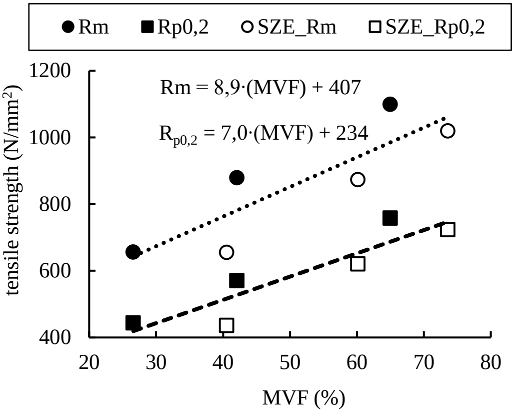

Fig. 2: the changing of the average strength parameters in the function of the MVF

The changing attitude of the total and uniform elongations in the function of the MVF is consistent with the changing of the strength, but on the contrary direction. It is worth mentioning that this linearity seems to be an incorrect approach for the elongation. It can be interpreted from the extrapolation of the elongation values to the 0% MVF, where those lead to uncertain results.

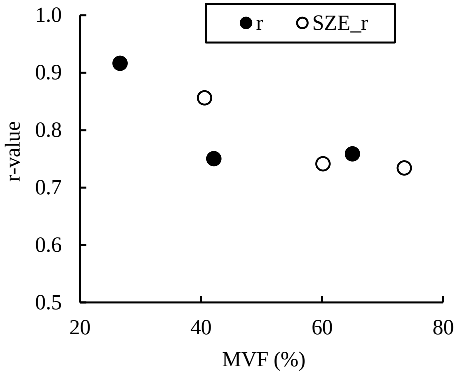

Fig. 3: the changing of the average anisotropy in the function of the MVF

The change of the anisotropy in the function of the MVF is different from the previous characteristics. It also decreases linearly if the MVF is less than 40-60% MVF, but it takes on a constant value above it (Fig. 3). This is due to the complex deformation mechanism of each phases, which works differently in the function of their ratio. At higher MVF, not only the ferrite matrix dominates in the deformation, thus it homogenizes the overall deformation.

3.2 Stress-strain curves

Thinking further the relationship of the plastic deformation behavior and the microstructure, the correlation between the MVF and the flow curve approximation possibilities was investigated in the next stage of my research.

The main object was to observe whether there is a relationship between the mechanic-based model parameters and the microstructure, or not. The parameters were determined by the least squares method (see Chapter 2.2).

My findings show that the nature of the applied hardening law can be traced in the model parameters' evolving also, in the function of the MVF. As an example, the strain hardening exponents show linear characteristics like the related uniform elongations (Fig. 4). Accordingly, the exponential changing of the strain multiplier parameters can be observed in the basically exponential functions, and the strength constants of the power laws are featured with the same (power law type) changing tendency. It means that the change of the hardening curve parameters effected by the MVF can follow the same character, which the fitting equations basically have.

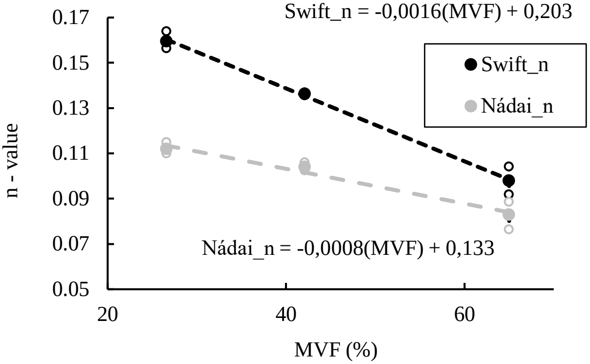

Fig. 4: the changing of the hardening exponents of the Swift and Nádai equations in the function of the MVF

3.3 Criteria of failure

3.3.1 Stress-based local necking criteria evaluation

Stress-based criteria are used in many cases when the classic forming limit diagram becomes unable to model the failure behavior of the material. The most popular occurrence is related to the necking of pre-strained samples, however its application on fracture forming limit, shear fracture and edge cracking evaluation is also widespread in the literature. Consequently, examples for different strain-stress transformation theories and the effect of the flow curve as well as the yield loci on the limit curve have been already seen for separate purposes.

In this area, my research work was focused on studying the effect of the flow (hardening) curve for both the traditional strain-stress transformation method [11] and for the simplified method from tensile tests' data by Levy and Tyne [12]. Latter authors proposed the possibility of drawing the entire forming limit curve from tensile tests data. Detailed analysis can be found in their researches about the behavior of the Nádai equation parameters and the newly introduced variables (e.g. Z parameter in Fig. 5), but the theory is still not compared with the transformation method and with different material models.

The necking limit values were determined by Nakajima test for the strain-stress transformations (see Chapter 2.3), and the former tensile tests result were used for the simplified method. Among the two plasticity features, the applied yield function was the Hill48 model uniformly, but the hardening curve model was changed. The calculated results obtained from the strain-stress transformation of the measured limit strains were compared to the theory of Z parameter and showed that the traditional transformation method has a higher flow curve dependence than the Z parameter-based calculations have. It is demonstrated in Fig. 5 for DC04 steel. (The characteristic is the same for all the investigated materials.) Besides, the Z parameter – and so the simplified limit curve – can not be calculated with the exponential flow curve approximations due to their nature, which results unrealistically high Z value at higher strains.

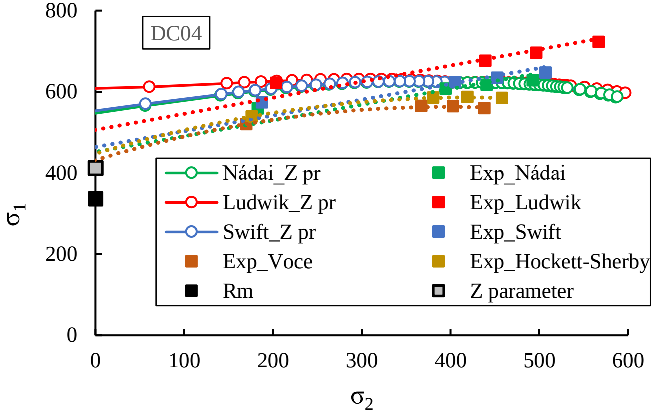

Fig. 5: the stress-based forming limit diagrams for different theorems and applied models (DC04)

3.3.2 Stress-based wrinkling limit criteria evaluation

Stress-based approaches are useful in wrinkling limit evaluation also. This is because of the conditions of the wrinkling formation in sheet metal forming, of which the most important factors are the tangential and the normal compression stresses. Although old theories in the continuum mechanics are known for the optimal blank holder pressure estimation as well as for the wave formation of a buckled element, there is still no really widespread, practical solution for the wrinkling limit evaluation of clamped surfaces, i.e. referring to the flange area during a deep-drawing process.

I have investigated many theories for describing the effect of the normal pressure on the wrinkling, considering the existing in-plane stress state also. Finally, using the Wang and Cao theory [15], a newly proposed wrinkling limit illustration manner was created, in which the wrinkling limit line – in contrast to the previous solutions – is defined as the function of the normal pressure. Fig. 6 shows the theoretical diagrams at three different blank holder pressures for the DP800 material. As it is expected, the higher the blank holder pressure, the higher the stress, which is necessary for wrinkling. The wrinkling limit curves were uniformly calculated by using the Hill48 yield criteria and the Swift hardening rule.

Using the aforementioned theory, the critical tangential stress, which is responsible for the wrinkling formation and the critical normal pressure, which is able to suppress wrinkling were imported as user defined result variables into the AutoForm® software. With a unique built-in module of the program (called 'traffic light concept'), the tracking capability of the wrinkling formation on clamped surfaces was solved in a simplified, user environment.

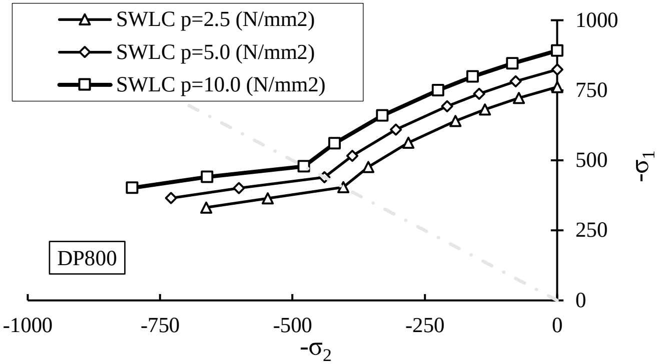

Fig. 6: the newly proposed stress-based wrinkling limit diagrams for different blank holder pressures (DP800)

3.4 Springback

This part of the dissertation is dealing with the geometrical defect of the applied sheets after V die bending process. The study is connected to the investigation of the springback evaluation itself, as well as to the observation of the newly applied tailor welded blanks' (TWBs') post-bending behavior.

In the first step, I have performed a deep investigation on the applied, practical springback evaluation methods and their developing possibility with advanced material characterization techniques. The main emphasis was on the definition of the material parameters (elastic modulus, plane strain stress, sheet thickness) as variables (in the function of the equivalent plastic strain), instead of constants. It is comprehensible if one sees the literature results about the elastic modulus' alteration, for example, but there is still no similar application in this environment. Secondly, the springback characteristics of laser welded 1-1 mm thick TWBs was investigated and the results can be seen in Fig. 7. Now the fact can be detected here that the springback is changing linearly in a transition zone, where the steepness depends on the constituent materials' grades and the bending geometry (punch corner radius). Note that the springback angles at the border of the transition zone reach the average angle change, which is the characteristic of the applied material.

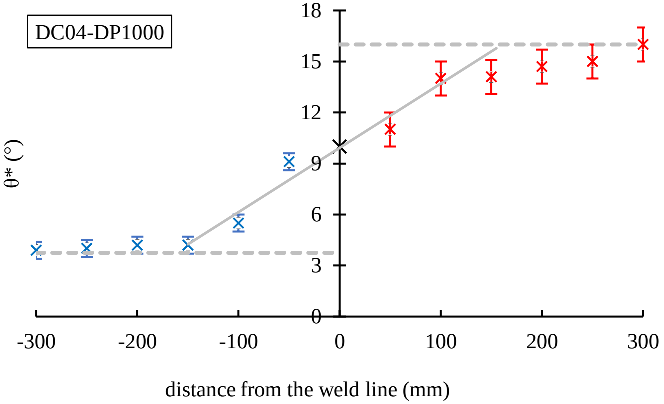

Fig. 7: experimental springback angles of DC04-DP1000 TWB for V die bending at 5 mm punch corner radius

4. Thesis, new scientific results

T.1. Linear correlation is determined between the average martensite content and the uniaxial mechanical properties (tensile strength, yield strength, uniform- and total elongation) using standard tensile and microscopic tests on DP600, DP800 and DP1000 sheet specimens. The assumed linear functions are given in the following form:

$$R_m = 8{,}9 \cdot (\mathrm{MVF}_{V/V\%}) + 407\,;$$
$$R_{p0,2} = 7{,}0 \cdot \left(\mathrm{MVF}_{V/V\%}\right) + 234\,;$$
$$A_g = -0{,}15 \cdot (\mathrm{MVF}_{V/V\%}) + 17{,}7\,;$$
$$A_{80} = -0{,}23 \cdot \left(\mathrm{MVF}_{V/V\%}\right) + 26{,}5\,.$$

In contrary, the plastic anisotropy expressed by the r-value does not show similar correlation with the microstructure [I], [II[, [III], [IV], [V], [VI].

T.2. The model parameters, in the Nádai-, Ludwik, Swift-, Johnson-Cook, Voce- and the Hockett-Sherby-type hardening curve approximations are changing in the function of the average martensite content. The parameters were calculated for the DP600, DP800 and DP1000 steels by the least squares method on the basis of the uniaxial tests' results. The strain multiplier model parameters' variance (K parameter in the Nádai, the Ludwik the Johnson-Cook and the Swift, b parameter in the Voce and N parameter in the Hockett-Sherby-equation) has the same characteristics in the function of the martensite volume fraction, as the equations' nature have. The variance is exponential in the exponential and power-type in the power law equations, thus the saturation phenomenon is fulfilled in the function of the martensite content also [VII], [VIII].

T.3. Stress-based forming limit curves for local necking related to in-plane stress condition for DC04, DP600, DP800 and DP1000 materials lead to different limit curve locations if different methods (strain-stress transformation and material-dependent parametric approximation) coupled with the Nádai, the Ludwik, the Swift, the Voce and the Hockett-Sherby strain hardening models as well as the Hill48 yield model is used in the calculations. The hardening curve dependence is definitely appeared in the strain-stress transformation technique. Whilst, the limit curves almost covered each other to the right from the plane strain state if the material-dependent parametric approximation was applied, so this approximation method has less flow curve dependence [IX], [X].

T.4. Using the Wang and Cao theory coupled with the Hill48 yield criteria and the Swift hardening rule, the criteria of wrinkling is illustrated as new wrinkling limit stress curves in the function of the blank holder pressure, in the main stresses’ coordinate system. The newly proposed curves are in good agreement with the deep-drawing experimental results [XI], [XII], [XIII].

T.5. The transition phenomenon is determined for the springback angles of 1-1 mm thick, laser beam welded DC04 – DP600, DC04 – DP800 and DC04 – DP1000 material pairs’ bending tests, perpendicular to the weld line in V die tools with 3 mm and 5 mm punch nose radius. The springback angle change is linear in the transition zone, until it reaches the average springback of the base materials. Furthermore, the straight lines referring to the transition zone have the following features: (i) its steepness increases if the strength difference between the base materials increases, thus the transition zone decreases along the horizontal axis; (ii); its steepness decreases if the punch corner radius – sheet thickness ratio increases, thus the transition zone increases along the horizontal axis. Furthermore, both the common strength of the components and the punch corner radius – sheet thickness ratio moves above the linear function in the vertical direction, thus they together increase the springback angle [XIV], [XV].

5. Possibilities of utilization and further improvements

During my PhD research work, I have investigated the formability and the failure criteria of thin sheets used in the automotive industry applying approximating models. One of the main aims of this PhD research study was the monitoring of the material behavior under mechanical loading to get to know the deeper physical background and the conditions of plastic instability in the sheet metal forming technologies. I performed experimental measurements and numerical simulations related to the most common failure modes, such as localized necking and wrinkling, as well as I studied the springback and shape accuracy, too.

I have examined how the existing relationship between the microstructure and the mechanical properties of DP steels can be extended, e.g. for the indentation load dependent microhardness results and for the uniaxial tension parameters. The tensile raw data were processed by the least squares method for calculating the best fit flow curve parameters, based on different theorems. Furthermore, the average martensite volume fraction dependence of the flow curve parameters, for five different models, were also investigated. According to my observations, noticeable relationship is existing between the microstructure and physical meaning of the model parameters as well. However, a deeper investigation on plastic anisotropy and r-value evolution can be included in this topic, too.

Using the flow curve parameters, the even today less prevalent stress-based forming limits were calculated by two different methods. Results show that different strain-stress transformation processes have divers effect on the given forming limits. In addition, I extended the stress-based criteria into the tension-compression state also, for wrinkling criteria evaluation. The critical tangential compression stress needs to create wrinkles and the minimum normal stress which is responsible for eliminating wrinkling were calculated by the energy-based theory of Wang and Cao and depicted in a novel wrinkling limit representation methodology.

The study of springback was carried out by rectangular V-die bending. To ensure the visibility of the bent geometry, different punch corner radiuses were applied on the different type of sheet metals. Therefore, both the geometrical and the strength effects were able to monitored, at least partially. I demonstrated that laser beam welded blanks bent perpendicularly to the weld line produce particular behavior near the welding zone. In a transition zone, none of the sheets make their usual springback, which is expected individually.

It is well visible (e.g. by the distortional hardening and the r-value’s not usual behavior) that further studying on the plasticity of the applied materials is an actual and full-of-possibilities topic. Both their yield function and flow-rules (either the associated, or the non-associated ones) evaluation holds new scientific results in the field of advanced material characterization. I am planning to work on new investigation methods’ developments in the future, for improving the current results in plasticity parameter calibration and in new failure methodologies.

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