Bending angle correction regarding sheet thickness

L.Durrenberger, P.Dietsch

ArcelorMittal Maizières, Voie Romaine, BP 30320, F-57283 Maizières-lès-Metz Cedex, France

laurent.durrenberger@arcelormittal.com

Abstract. V-bending tests realized according to VDA 238-100 standard allow determining the bending angles (before and after springback) of a steel sheet of thickness th_0 and the fracture strain in plane strain. The aim of the present study is to propose a correction law for bending angle before springback allowing to predict the angle corresponding to another sheet thickness th (the bending angle increases with the decreasing thickness). This correction allows comparing steels bendability even if experiments are performed with different sheet thicknesses. Another interest is to be able to predict bending angles for sheet thickness mentioned in customer products specifications.
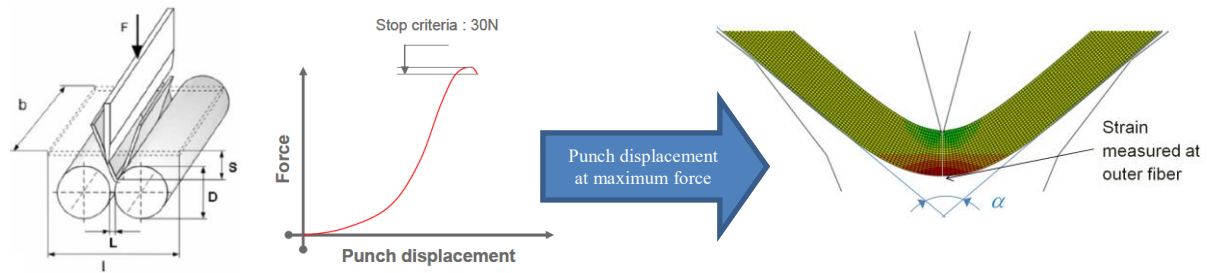
1. General approach

The present study is based on VDA 238-100 standard [1] aiming at determining the bending angle of metallic materials. For a given material, bending angle depends on the product thickness and is not an intrinsic material characteristic. The aim of the present study is to propose a correction law for bending angle before springback allowing to predict the angle corresponding to another sheet thickness.

The correction to apply depends on the considered bending angles; before or after springback. Daimler proposed a relation to correct bending angles after springback [2], but no correction has been proposed until now to correct bending angles before springback.

A numerical approach has been chosen to generate the evolution of the bending angle before springback, called here-after α, as a function of the maximum strain observed in the bending area according to VDA 238-100 testing conditions. In the numerical simulation, α is measured between the two straight sections of the sample (see Figure 1). Once a fracture of the sample is experimentally observed, this maximum strain corresponds to the fracture strain in plane strain.

According to VDA 238-100 standard, fracture initiation is detected by a 30N load drop during the bending test. Cheong et al. [3] have for instance proposed a special roll shape allowing the use of Digital Image Correlation during the test. In this study, the experimental displacement at maximal force measured experimentally is then used in an ABAQUS implicit model with fine mesh through thickness and plane stain elements (see Figure 1). Using this approach, FEA acts as virtual measurement tool that provides strain value at failure initiation, or failure strain. The present study is based on the assumption that fracture strain derived from VDA 238-100 bending test does not depend on the steel thickness.
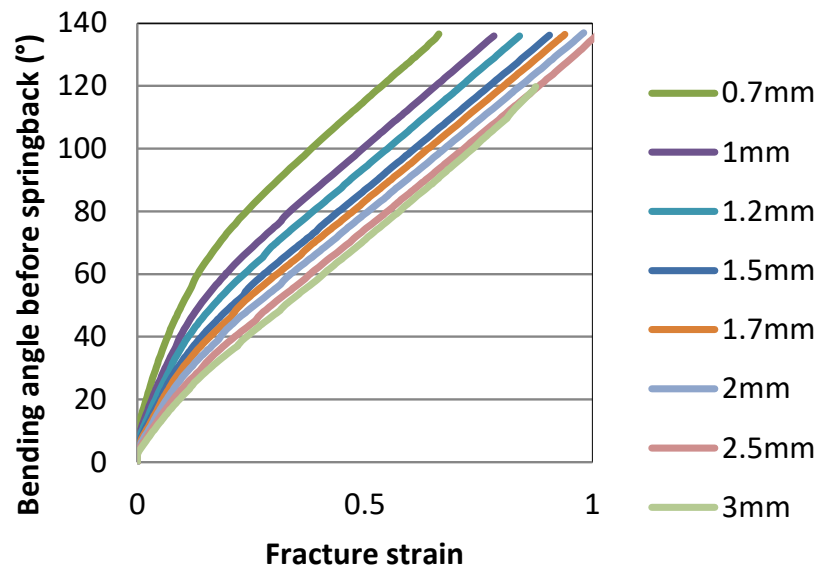
Figure 1. VDA 238-100 bending test: illustration of combined experimental/numerical approach for failure strain determination.

A large panel of steel grades -AHSS (>600MPa) / UHSS (>980MPa)- has been considered in the present study, including a virtual material with a perfectly plastic behavior in order to consider a material without uniform elongation (see Table 1).

Table 1. Mechanical properties of the 12 steel grades considered in numerical simulations of the VDA 238-100 bending test.
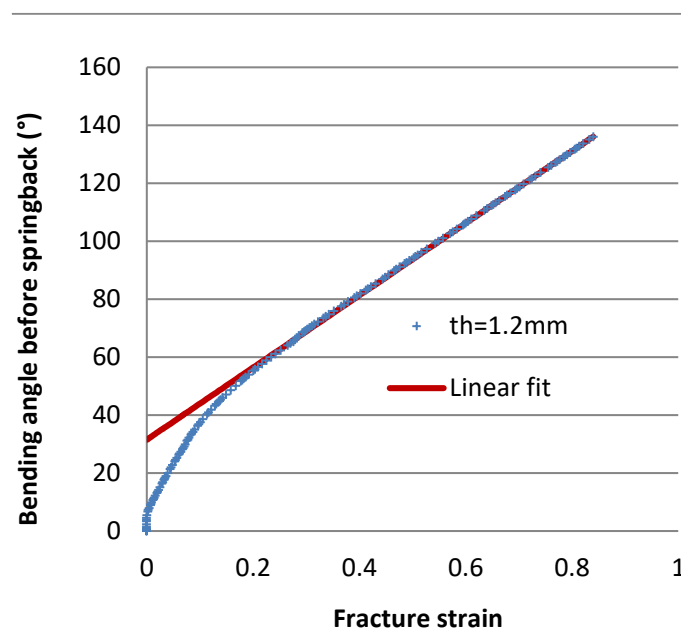
Material	YS (MPa)	UTS (MPa)	UEL (%)
Steel I	370	605	16.0
Steel II	535	785	10.0
Steel III	505	825	23.0
Steel IV	615	835	10.0
Steel V	820	1030	4.5
Steel VI	730	1050	6.5
Steel VII	890	1070	2.5
Steel VIII	725	1110	11.5
Steel IX	975	1200	5.0
Steel X *(perfectly plastic)*	975	975	0
Steel XI	1200	1500	3.5
Steel XII	1455	1870	4.0

The Swift-Voce model [4,5] has been used to describe the materials hardening behavior in numerical simulation. For all steels, the bending behavior of 8 thicknesses has been simulated: 0.7 – 1 - 1.2 – 1.5 – 1.7 – 2 – 2.5 and 3mm (example of Steel IV in Figure 2).
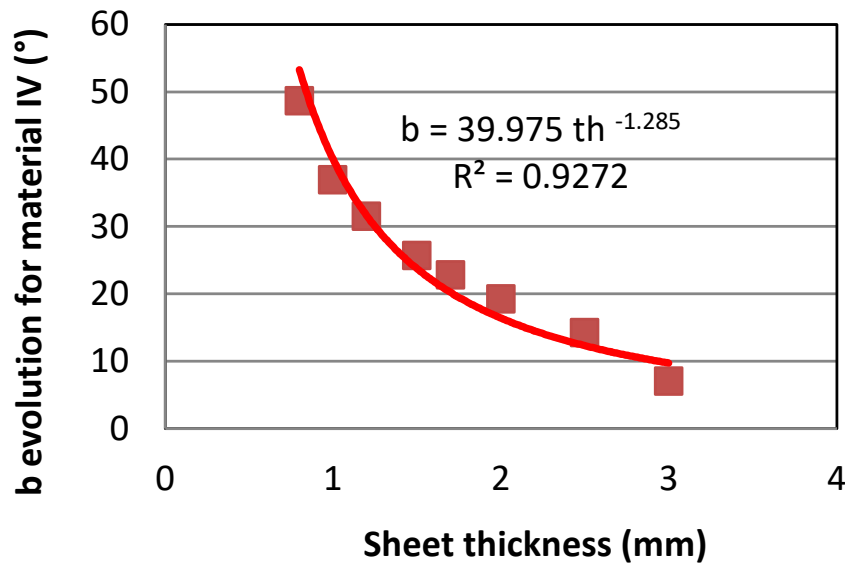
Figure 2. Evolution of the bending angle before springback α as a function of the fracture strain in plain strain (ε) for different sheet thicknesses - Example of Steel IV.

If the fracture strain in plane strain ε exceeds a value about 0.1 (the exact value depends on the steel grade), a linear approximation $\alpha=a*\varepsilon+b$ is suitable to model the evolution of the bending angle as a function of ε (Figure 3).

Figure 3. Above a fracture strain in plain strain of ~0.1, the bending angle before springback α can be directly expressed as a linear function of the fracture strain - Example of Steel IV for a sheet thickness of 1.2mm.

For a given steel grade, we can note that the slope 'a' remains almost constant for all thicknesses (see Figure 2). Conversely, the y-intercept 'b' depends on the steel grade and sheet thickness. As illustrated in Figure 4, the evolution of 'b' as a function of the product thickness can be modelled using a power law.

Figure 4. Evolution of '*b*' as a function of the product thickness expressed by a power law - Example of Steel IV.

As a result, the following relation describes the evolution of the bending angle before springback α as a function of the fracture strain in plain strain ε and the product thickness th:

$$for\ \varepsilon > 0.1, \qquad \alpha = a(product).\varepsilon + b_1(product).th^{-b_2(product)} \qquad (1)$$

where a, b_1 and b_2 are three constants values depending on the considered steel.
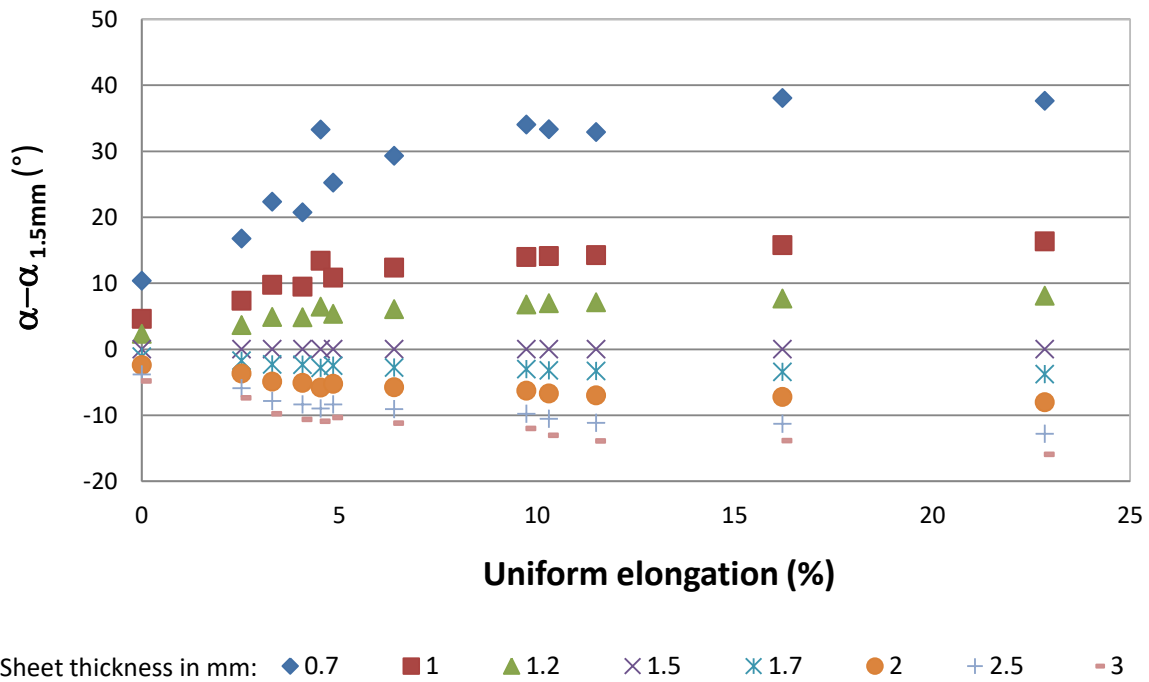
Assuming that fracture strain in plane strain conditions measured in VDA 238-100 bending test is not affected by the sheet thickness, we can express the difference of bending angle between the corrected bending angle α with the measured bending angle α_0,

$$for\ \varepsilon > 0.1, \qquad \alpha - \alpha_0 = b_1.\left[th^{-b_2} - th_0^{-b_2}\right] \qquad (2)$$

where th is the sheet thickness corresponding to α and th_0 is the sheet thickness corresponding to α_0.

Thanks to Equation (2), it is possible to calculate $\alpha - \alpha_0$ for all the 12 steel grades considered in the present study with the interest to be independent on their maximum strain at fracture.

As illustrated in Figure 5, the correction of bending angle to apply between α and α_0 (α_0 corresponding here to a sheet thickness th_0 of 1.5mm) is directly depending on the uniform elongation value of steel grades. Steel grades with high uniform elongation values (like Steel III) need more correction than steel grades with low uniform elongations values (like Steel XI).

Figure 5. Evolution of the angle correction ($\alpha-\alpha_{1.5mm}$) as a function the uniform elongation values for 8 sheet thicknesses varying from 0.7mm to 3mm.

2. Phenomenological modelling

Data shown in Figure 5 can be fitted by the following power law,

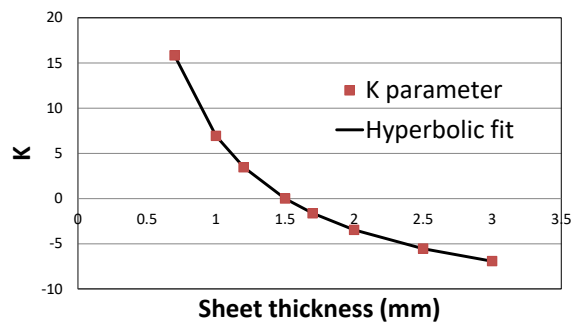$$\alpha - \alpha_0 = K(th).[UEL(\%) + C]^n \tag{3}$$

where $K(th)$ is a coefficient depending on the sheet thickness, C and n are two constants.

The evolution of K with respect to the sheet thickness th can be fitted by a hyperbolic function (Figure 6), Equation (4). Assuming that if the corrected and measured thicknesses are equal ($th = th_0$), the correction should be equal zero, Equation (5).

$$K(th) = k_1 + \frac{k_2}{th} \tag{4}$$

with $K(th_0) = k_1 + \frac{k_2}{th_0} = 0$ $\qquad\qquad$ (5)

where k_1 and k_2 are two constants.

Figure 6. Evolution of K as a function of the sheet thickness. Data are correctly fitted by a hyperbolic function.

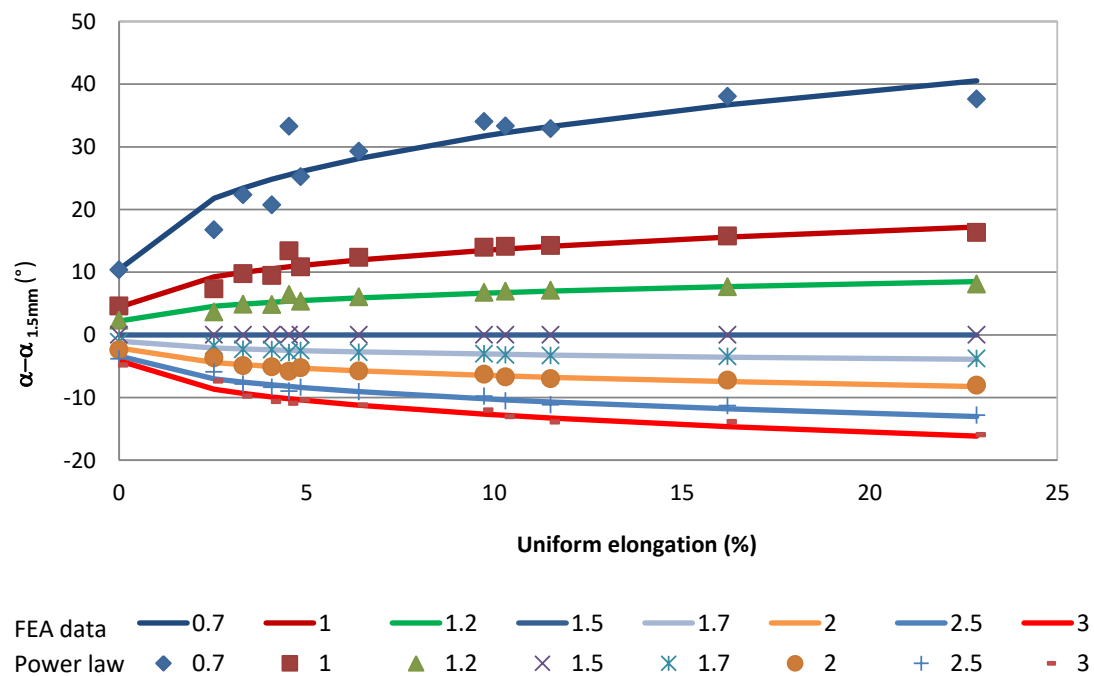Combining Equations (3), (4) and (5), we finally obtain the following relation,

$$\alpha = \alpha_0 + k_1 \left[1 - \frac{th_0}{th}\right] . [UEL(\%) + C]^n \tag{6}$$

Adjusting parameters k_1, C and n have been identified using a least square method on data shown in Figure 5, see Table 2.

Table 2. Value of the adjusting parameters.

k_1	C	n
-13.852	0.22	0.292

As illustrated in Figure 7, the predictions of Equation (6) are in very good agreement with numerical data.
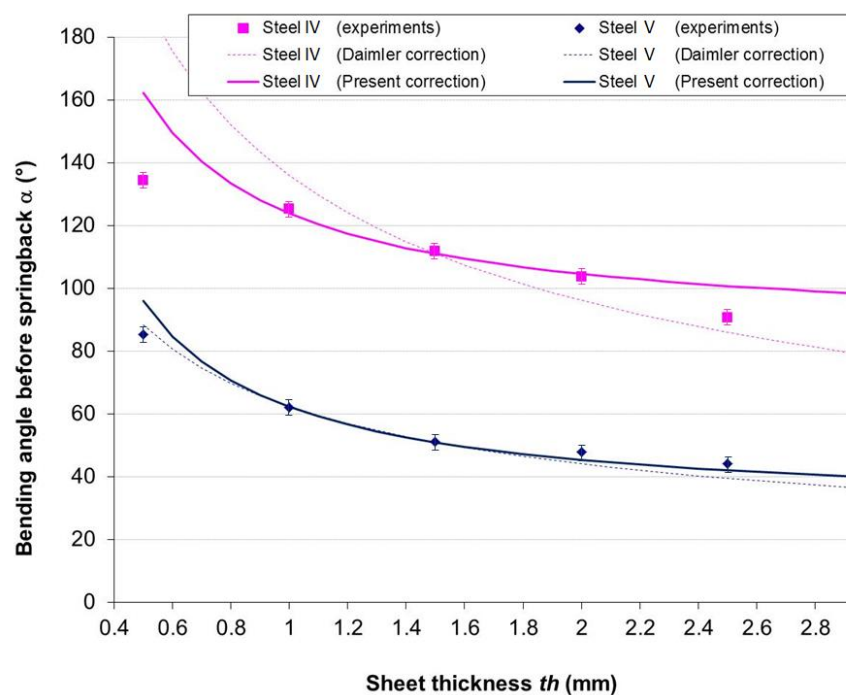

Figure 7. Comparison between the analytical prediction of Equation (6) (solid lines) with FEA data (points) for 8 sheet thicknesses.

3. Validation

The proposed correction law for bending angle before springback, Equation (6), has been applied on two steel grades ('Steel IV' and 'Steel V') whose bending angles have been measured for different sheet thicknesses. These experimental data have been obtained from initial 3mm thick materials which have been symmetrically grounded to obtain lower thicknesses. The approach proposed in VDA 238-100 – Annex D was used to evaluate the experimental bending angle before springback.

As shown in Figure 8, the predictions of Equation (6) are in good agreement with experimental data except for thicknesses lower than 0.7mm. Here, the measured thickness th_0 has been considered equal to 1.5mm.

Daimler proposed a simple relation $\alpha = \alpha_0 \sqrt{th_0/th}$ to convert bending angle after springback. Figure VIII shows clearly that the correction to apply before and after springback is not the same.

Figure 8. Models predictions (lines) compared to experimental data (points) of 2 steels.

As a conclusion, bending angles before springback can be corrected using the relation $\alpha = \alpha_0 - 13.852 \left[1 - \frac{th_0}{th} \right] . [UEL(\%) + 0.22]^{0.292}$.

References

[1]   VDA 238-100, June 2017. Plate bending test for metallic materials
[2]   Mercedes-Benz standard DBL 4093, Karosserieteile aus pressgehärteten Stahlblechen, 2015.
[3]   Cheong, K., Omer, K., Butcher, C., George, R., Dykeman, J., Evaluation of the VDA 238-100 Tight Radius Bending Test using Digital Image Correlation Strain Measurement, Proceedings of 36th International Conference of the International Deep Drawing Research Group (IDDRG 2017), Journal of Physics: Conference Series, 896, 012075, pp.1-9.
[4]   X. Lemoine, How to accurately model AHSS in numerical stamping simulation, IDDRG conference, Graz, 2010, pp. 819 – 828.
[5]   X. Lemoine, S. Sriram and R. Kergen, Flow curve determination at large plastic strain levels to accurately constitutive equations of AHSS in forming simulation, ESAFORM Conference, Belfast, 2011.