Characterization of elasto-plastic transition of sheet metal by using large-scale four-point bending test

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Abstract. The elastic properties of a material do play an important role in the spring back behaviour of sheet metal and have a dominant influence on the depth of where the bending tool has to go. In industry, the elastic behaviour is often approximated to a pure linear behaviour defined by two coefficients: Young’s modulus (E) and yield stress (Re). This modelling hypotheses result in geometrical errors in the angle and flange lengths of bended part. In order to better determine material behaviour at very small strains, a large-scale four-point bending test machine is presented in this study. Generating pure bending and measuring the residual radius allow observation of the transition between elastic and plastic deformation behaviour. By deforming the test beam in the supposed pure elastic area, it appears that the pure elasticity behaviour of the material is indeed non-existent. Plastic strains can be detected as soon as the very first bending of the sample, at very low equivalent stress well under usual accepted elastic yield stresses. Perspectives are addressed in order to solve this difficulty, which hinders the possibility of correctly simulating the bending process, particularly with regard to tight geometry requirements.

1. Introduction
In sheet metal forming industry, it is essential to reduce non-productive time but also to reduce the quantity of wasted material per produced part. The former objective is of paramount importance in forming processes like bending that allows the production of small series of parts. In such cases, the price itself and the time cost of trial and error become non-negligible compared respectively to the market cost of the part and its production time. These difficulties also go hand in hand with the generation of a lot of wasted metal and result in an over consumption of raw material.

Three-point bending is now seen as an easy and reliable process that can soundly be integrated in general production. Indeed, in a growing number of places, it is becoming more and more common to see machined parts being replaced by bended parts. In these cases, bended parts have to support extra engineering functionalities which can be fulfilled with the control of supplementary geometrical specifications. Main target is not anymore to aim for an angle with a given tolerance but also for defined sides’ dimensions with strict tolerance regarding process’ usual capabilities.

Almost all bending machine vendors are investing into systems that allow directly measuring the spring back on the fly in order to correct it in real-time. However, this solution does not provide the means to respect the supplementary constraints imposed on the formed part, namely the length of its sides. Therefore, one way to control both the angle and sides’ lengths is to conduct an optimisation that aims to define the initial width of the flank and the machine control parameters, using some design of experiments. This optimisation can be carried out using finite element tool to simulate the behaviour of the flank under the effect of boundary conditions modelling machine thrust. To generate accurate
predictions, it is essential to have an accurate modelling of the material behaviour. Nevertheless, until now and as far as finite element simulations are concerned, the constitutive behaviour models do not allow for a prediction with sufficient accuracy. Air bending induces important spring back that can be affected by many parameters of the material [1]. Among all of them, so-said elastic parameters, Young’s modulus and yield stress are first order determinants of the elasticity behaviour of the blank.

2. Influence of Young’s modulus and yield stress on bending simulation
To study the bending process sensibility upon the elastic parameters, FEM Abaqus software was used to simulate a bend obtained with a 12 mm opening die and a punch with a radius of 1.5 mm on a 2 mm steel sheet metal. As three-point bending is used on parts with an important length and width relative to the thickness dimensions, it allows to consider plane strain in the bended section. Therefore, 2D simulation and symmetrical conditions are acceptable simplifications to optimize time simulation vs. accuracy insofar as the aim was not to simulate any 3D effect such as anticlastic curvature [2] but to evaluate at least the influence of each elastic material parameters taken separately. Different courses of the punch were imposed to reproduce real cases where the corresponding angle was measured. The modelling of the material was characterized by a Young’s modulus of 210 GPa and a yield stress Re set at 130 MPa. The elastic behaviour is therefore assumed to be linear isotropic. The Von Mises criterion is used to determine the yield strength and isotropic hardening based on the equivalent stress-strain curve described by the true stress-true strain curve obtained in tension.

Mean corresponding material parameters were identified on a mild steel DC03 sheet metal used to produce the real part. A first set of simulations (Figure 1) was provided to study the dependence of the final angle with Young’s modulus and yield stress parameters. The variations on these parameters are introduced to reflect the experimental measurement uncertainties that prevail when they are identified.

![Stress mapping obtained during the 2D simulation of a bend on DC03 metal sheet of 2 mm with a 12 mm opening, a 3 mm diameter punch and a 12 mm stroke after tooling removal.](image)

Figure 1. Stress mapping obtained during the 2D simulation of a bend on DC03 metal sheet of 2 mm with a 12 mm opening, a 3 mm diameter punch and a 12 mm stroke after tooling removal.

Plotting of the variation between final angles obtained with two numerical simulations with a different E value shows that variation on E modulus alters the prediction enough to limit its predictive reliability. Rather small, this variation is already too big to be consistent with imposed tolerances on the industrial process. In fact, the targeted tolerance on the angle is ±0.2°. As the two parameters are independent, the error can be cumulated, and it becomes clear that the prediction cannot be seen as reliable.
Simulations have also been performed to determine the influence of yield stress $R_e$ (Figure 3). The yield stress uncertainties also have similar effects on the angle determination.

The effects of uncertainties on the elastic parameters can be cumulatively added resulting in hazardous estimation of bending angle on which it will be impossible to base the industrial bending operation optimisation.

3. Definition of parameters based on tensile test
The above results show the necessity to provide unquestionable identification of elastic parameters to provide, with the help of the simulation, an accurate prediction of bending operations. For this purpose, two materials were selected - DC04 and DC03, steels defined for cold forming processes. The objective is to focus the identification process of elastic parameter and to determine a possible deterministic way of obtaining univocally elastic parameters that would increase reliabilities of finite element simulation.

The stress-strain curve, obtained by tensile test (Figure 4), for the two selected materials is the usual support of elastic parameters identification. These tensile tests have been run a 5569 Instron machine and a 12.5 mm width extensometer to measure the strain, the strain rate was set at 7 mm/min. For this we use sample from the sheet metals cut in different directions, such as, L for longitudinal (in the laminated direction), D for diagonal (45° to the laminated direction) and T for transversal (90° to the laminated direction). Each time, three samples were tested. In the figures under, only one of the samples is represented as the results were consistent.

The identification process of the elastic parameters is rather trivial. After identifying a linear stress-strain dependency, two yield stress values would respectively be set – 190 MPa for DC03 and 135 MPa for DC04.
A closer examination of the strain region between 0 and 0.004 (Figure 5), gives another possibility to define elastic limit Re0.2 of a material. This value is provided first by sheet metal suppliers but could also be determined directly by the experimenter. The method for determining the elastic limit Re0.2 [3] is to determine the portion of the curve on which elastic behaviour is considered. In one way or another, a linear regression is performed to obtain the slope of the line that approximates this portion of the curve. This slope is therefore the considered Young’s modulus. To obtain the elastic limit, a straight line is drawn through (0.002) with the same slope and its intersection with the stress-strain curve is determined. Corresponding stress is the Re0.2 value that can be used as yield stress. This is nevertheless a little fuzzy insofar as plasticity events have already occurred in material. Note also that the use of such value in Abaqus will immediately introduce errors due to the fact that as long as the elastic limit is not reached, the behaviour is assumed to be perfectly elastic.

This induces that the determination of yield stress for DC03 is very dependent on the identification process. For DC03, the determined yield stress is 190 MPa and for DC04, yield stress is 140 MPa. Thus, for DC03, if we take the value from Figure 5, it appears that Re0.2 would be 182 MPa, that is to say under the value of Re that has been defined in the Figure 4 (190 MPa). Furthermore, the linearisation approximation induces Young’s modulus approximation that also depends on the experimenter and has a direct effect on the yield stress determination.

Furthermore, even approximating these curves as linear seems inappropriate with respect to the accuracy to conduct a simulation of bending. Usual method to define Young’s modulus in the industry for those materials is to take the so-called part of the curve, here between 0 and 100 MPa for DC04 and between 0 and 120 MPa for DC03, and to use the directing coefficient of the approximate line as the E modulus of the material. This has been represented in Figure 6a and Figure 6b.
Figure 5. Magnification of the curve at the transition from purely elastic to elasto-plastic behaviour to determine Young’s modulus and yield stress at 0.002 strain for DC03 and DC04.

Figure 6a. Determination of Young’s modulus based on the measures between 0 MPa and 130 MPa.

Figure 6b. Determination of Young’s modulus based on the measures between 0 MPa and 100 MPa.

Young’s modulus is usually not provided by sheet metal suppliers, but as mentioned previously is a necessary parameter to be defined in the simulation. If we compare the estimated Young’s modulus with what is often given as a standard for steel, 210 GPa, measured in i.e. 184.5 GPa ±2.5 GPa for DC03 and 139.4 GPa ±2.6 GPa for DC04, it can be concluded that a simulation ran with standard values adjusted to the generic parameters provided by suppliers’ certificates will not lead to an exploitable prediction of the results for optimising industrial process.
Table 1: Comparison of the different values of Young’s modulus and yield stress obtained with the different methods.

| Method                              | DC03 Young’s modulus GPa | DC04 Young’s modulus GPa | DC03 Yield Stress MPa | DC04 Yield Stress MPa |
|-------------------------------------|---------------------------|--------------------------|-----------------------|-----------------------|
| Tensile curve determination         | Not evaluated             | Not evaluated            | 190                   | 130                   |
| Using strain of 0.2 %               | 182                       | 168                      | 182                   | 135                   |
| Linear approximation between 0 MPa and 100 or 120MPa | 184.5                     | 139.4                    | Not evaluated         | Not evaluated         |

Table 1 shows how the values defining the elastic behaviour of a sheet metal is questionable and can be considered as random. The values summarised in Table 1 are varying sometimes by almost 17% for the Young’s modulus and by around 5% for the yield stress. The tendency of approximations is also not all the time an over neither an under estimation. This may have a real impact on the quality of the predictions and may lead to wrong estimations of the bend results.

4. Observation of the elasto-plasticity with a large-scale bending bench

Showing all the possible approximations of the different elasticity parameters with a tensile test leads to finding an unequivocal way to determine them. An in-depth understanding of physical processes occurring at very small stresses and strains states are therefore necessary to achieve high accuracy in the predictions.

In that purpose, a large-scale bending bench has been developed. With this bench, it is possible to generate small stress into the sample while generating a large global displacement which is easier to observe and measure.

![Figure 7](image-url)

Figure 7. Concept of the first version of the large-scale bending bench. 1 Punches, 2 V-bock, 3 Sheet metal sample, 4 Laser sensors, 5 force sensors. Dimensions in millimetres.

The bench is composed of two fixed punches, denoted (1) in Figure 7. The upper beam playing the role of a large V-block and denoted (2) will be moved up and down. The displacements will be made in steps. In the first step, the two points are moving to a given position and in the subsequent step, the points are moved back to the starting position. The punches strokes are incrementally increased after each step to increase the deformation. After each step, the residual displacement of the sample part (3)
is finely measured with three laser sensors (4). During the tests force sensors (5) will measure the force applied on each point (fix and moving). This will allow to evaluate the symmetry of the system and to calculate the applied moment on the sample.

The primary reason for choosing this type of test is because it provides the advantage of generating a constant load over a large portion of the test sample. The motion of the two points from the upper beam generates two forces that are equal and symmetrical. The resulting moment exerted on the sample is then constant over the distance between the two fixed points, as shown in Figure 8.

![Figure 8. Evolution of the moment along the sample. The constant moment is between the two fixed punches (corresponding the dimension 346 mm) and the moment is null at the contact of the two moving points (at 0 mm and 856 mm).](image)

Preliminary tests were performed on different samples of a DC04 sheet metal (Figure 9), for which residual displacements measured by the central sensor were plotted versus the calculated applied stress for a given stroke of the punches.

The “applied” stress, used as the horizontal axis of the graph (Figure 9) was calculated based on the beam theory [4] and the geometry of the bending bench.

\[
\sigma = -\frac{M_{yz}}{I_{gz}} \cdot y
\]  

(1)

\(M_{yz}\) is the moment calculated based on the force measured by the sensors and the distance taken to calculate the moment is the one between a moving a fix and a moving point, the \(y\) distance corresponds to a point in the height of the sample that needs to be evaluated. The zero value corresponds to the middle layer of the sample. \(I_{gz}\) is calculated according to equation (2) where \(b\) is the width of the sample (35 mm) and the \(h\) is the thickness of the sample (2 mm).

\[
I_{gz} = \frac{bh^3}{12}
\]  

(2)

The value of the stress plotted on Figure 9 corresponds to the value for \(y = h/2\). This corresponds to the higher stress applied on the sample.

It is then possible to observe residual displacement that is the consequence of plastic strain obtained even if the average stress in the sample is far below yield stress whatever the method to obtain it. Here \(R_e = 125\) MPa is considered for DC04. These results confirm that considering the material as purely elastic before reaching the yield stress has to be questioned in the objective to obtain accurate simulation of bending starting with the prediction of spring back.
Figure 9. Residual displacement of the central point measured by the central laser after each descent of the crossbar versus tensile stress at the sample surface for DC04.

5. Conclusion and perspectives
This study aims to answer the problem of obtaining good parts immediately in 3-point air bending industrial process.

The answer to this problem lies in the use of finite element simulations. It is then shown that the necessary accuracy on the geometry of the simulated part cannot be obtained if one uses the parameters of the elastic behaviour obtained by the usual processes of identification from tensile tests or by being satisfied with the values provided on the material files by the raw material suppliers. In fact, considering the material as purely elastic in this region of deformation, suggests that all parts of the sheet metal are deforming in the same way.

In order to closely study the behaviour of the so-called and therefore hypothetic purely elastic stage, a bending bench has been developed. Several tests have been conducted below the ‘apparent’ elastic yield stress with results showing already permanent changes of shapes.

Therefore, another way to describe the material behaviour is to consider very low strains since the beginning of the deformation. Considering the heterogeneity of the sheet metal is certainly the prerequisites for defining models that can reproduce the plasticity that occurs at the smallest deformations.

Sheet metal is composed of grains with different orientations [5], it is then highly improbable that all the grains are behaving uniformly under an applied stress. This heterogeneity should be considered in the modelling in order to achieve the targeted accuracy.

As a follow-up study, a hybrid compartmented model [6] which takes into account this heterogeneity will be integrated in the bending simulation. The model mitigates the uncertainties of characterising the elastic part of the material by approaching the material as full elasto-plastic. It is believed that it will allow us to reach a satisfactory description of the first part of the curve to be able to correctly simulate residual deformation phenomena even at very small deformations.

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