Lightweighting in Automotive Industry
Using Sheet Metal Forming – Advances and Challenges

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Abstract

Weight reduction in automotive industry requires forming of light weight and high strength materials at room temperature as well as at elevated temperatures. This requirement presents new challenges in material characterization and formability, lubrication, die materials and design, process simulation and prediction of springback, press design and operation as well as in quality control.

This paper reviews some of the recent research results in these areas. Specifically, methods will be discussed on how to (a) evaluate the formability and quality of incoming sheet material, (b) estimate the flow stress of sheet materials using uniaxial tensile and biaxial bulge tests, (c) evaluate the performance of lubricants and the coefficient of friction in forming Al and AHSS using the Cup Draw Test, (d) prepare
input data for reliable process simulation using commercially available Finite Element software, to predict and avoid forming defects and springback, (e) use the capabilities of the servo-drive presses and the CNC hydraulic cushions, and finally (f) how to reduce scrap rate and increase productivity in forming difficult to form AHSS and ultra-high strength Al alloys.

1. Introduction

To achieve weight reduction in sheet metal forming (stamping) recent research studies focused on (a) forming of AHSS (DP600, DP980, CP800, TRIP1180, DP1200) using servo drive presses with CNC hydraulic cushions, (b) hot stamping of Mn-B steels, (c) cold and warm forming of Al alloys (5xxx, 6xxx and 7xxx series), (d) improvements in the evaluation of material properties (true stress/strain or flow stress curve) as well as the use of new lubricants.

While R&D is undoubtedly very important to make advances in reducing the weight of sheet metal structures, it is equally important to apply the research results to practical shop floor operations, to reduce defects, improve quality and reduce costs. The use of advanced materials, while they have the potential of reducing weight, also presents new challenges due to the material’s higher strength and low formability compared to conventional steels. Challenges include: (a) inconsistency of incoming material properties, (b) fracture during forming, (c) higher contact pressure and temperature rise during forming, (d) higher die wear leading to reduced tool life, (e) higher forming load/press capacity, and (f) large springback leading to dimensional inaccuracy in the formed part [1]. The complexity of achieving light weight, illustrated in Fig 1, includes the consideration of design, material selection, new processes, new lubricants and new presses and toolings. It is seen that the OEM must consider several important factors such as safety regulations, fuel consumption, pollution, customer/society perception, costs as well as profit from sales.
2. Advanced Materials

The use of AHSS has been increasing steadily in automotive stamping. New AHSS alloys (TRIP, TWIP) may replace some of the Hot Stamping applications. Fig 2 shows three generation of the most commonly used AHSS materials in vehicle construction. Companies around the world attempt to expand the application of very high strength Dual Phase steels. For example, DP980 and DP1200 are now routinely used in stamping. Selected models of Nissan already have B-pillars formed from DP1200 steel. In Japan, development work is in progress for forming 1400 MPa material for producing structural components. As expected, low formability, springback as well as tool/press deflections are issues to be considered for obtaining quality parts.
The most commonly used Al alloys in automotive industry include 5xxx, 6xxx series that are largely used to manufacture closures, i.e. doors, hoods, trunk lids, etc. The high strength alloys, i.e. 7xxx series, must be formed at elevated temperatures and they are being investigated for cost effective application. Fig 3 illustrates the virtual comparison of a B-pillar, formed by hot stamped boron steel and from Al 7075-T6. Results showed same crash performance for both materials while the mass saving in case of using Al 7975-T6 is 40%. Fig 4 illustrates a production part made from 7xxx aluminum, a door side crash beam, used in BMWi8.
3. Determination of material properties

In using advanced materials, advanced methods are also required for determination of material properties and formability. Moreover, preparation of accurate material model and simulation input are more challenging for these materials. A common problem for new generation of AHSS is that the material properties and formability of the same material can differ from supplier to supplier and even from batch to batch. Therefore, the stamping industry needs reliable and economic methods to determine the material properties for each batch of material they receive from the supplier. Various experimental and evaluation techniques are being developed to improve the accuracy and reduce the cost and the time for conducting these tests.

3.1 Flow Stress (True Stress/True Strain) Curve

Tensile test is the most common test for determination of the mechanical properties. The engineering stress/strain curve, Lankford coefficient (R-values), and elastic modulus of the material can be determined through this test. However, in the tensile test the material is deformed in uniaxial loading state and the strain path is linear. As a result, the strain at fracture is small. In most sheet metal forming applications, during the forming of the sheet, the strain path is nonlinear and it is a combination of uniaxial, plane strain, and biaxial strain state. Therefore, the material properties obtained from the tensile test may not accurately represent the behavior of the material in a real stamping process.

Hydraulic bulge and viscous pressure bulge test (VPB) allow the determination of flow stress under balanced biaxial tension. Thus, compared to uniaxial tensile test, higher range of strain can be obtained. The VPB test has been introduced by Gutscher et al.
[2], as a new version of the hydraulic bulge test. In the VPB test, the fluid is replaced by a viscous material and therefore there is no splashing of the fluid after the burst of the sample in this test, Figure 5.

![Figure 5: Schematic of the VPB test as conducted at CPF-Ohio State University](image)

In the VPB test, used at CPF-Ohio State University, the pressure and the dome height is measured during the test. Then, through inverse analysis, the flow stress curve is determined. Another method, as developed at IFU-Technical University Stuttgart, involves the use of Digital Image Correlation (DIC) to measure the dome height and strains in the deforming sheet during the test, Figure 6.
The VPB test, similar to hydraulic bulge test, can be used to estimate the formability of the sheet material, when the test is conducted until the sample has fractured (or burst), Figure 7. The height of the bulge at bursting (fracture) is an indication of the material formability, even though the deformation is equi-biaxial and linear while in stamping the strain path is usually non-linear.
Although the VPB test can provide the material data for higher strain values compared to the tensile test, the VPB test is not sensitive at small strain values and cannot provide accurate flow stress data in strain range close to yield point. Therefore, a new methodology is proposed in this paper to determine the flow stress data from combination of the tensile test and the bulge test. In this method, the yield stress is determined from the tensile test. Then this value is converted from the engineering value to the true stress value using formula (1):

\[ \sigma_{true} = \sigma_{eng}(1 + e) \]  

(1)

Where \( \sigma_{eng} \) and \( e \) are the engineering values of the yield stress and yield strain. This true yield stress is used with other data points obtained from the bulge test to represent the flow stress of the material using the power law and \( K \) and \( n \) values (\( \sigma = K \varepsilon^n \)). Fig 8 shows the flow stress curves for 1.2mm DP980 determined using tensile test, bulge test and the new combined method described above. As shown in this figure, the strain at fracture obtained from tensile test is about 0.07 while the VPB test provide the flow stress data up to strain=0.35. However, the VPB test cannot determine the flow stress data for strain values less than 0.03. The dashed line is the flow stress curve calculated from the combined method and representing the material data from yield point up to high strain values.

![Figure 8: Example - Flow stress curve for 1.2mm DP980 obtained from the VPB test, the tensile test and the new proposed combined methodology.](image)
3.2 E-Modulus and Anisotropy

In isothermal FE simulations, where the temperature generation due to the strain energy is not considered, beside the flow stress data, E-modulus and the Lankford (anisotropy) coefficients are other important parameters that affect the FE simulation results. Currently, these two parameters are usually determined from tensile test considering several assumptions.

a) Both the E-modulus and the anisotropy parameters are determined with the tensile test, i.e. at relatively small strains.
b) It is then assumed that these values, obtained from the tensile test remain constant throughout the deformation that takes place during practical stamping operations. Nearly all commercially available FE software packages for sheet forming process simulation work with these assumptions.

It is to be expected, as shown in many simulations conducted at CPF, that both: anisotropy and E-modulus values vary with the deformation of large strains. Especially the E-modulus, that greatly affects springback predictions, may not remain constant with varying strains and strain paths that occur in practical stamping operations. In conducting simulations, it is necessary to consider the validity of the assumptions, discussed above even though there is no immediate test method to reduce or eliminate the assumptions made in the industry as well as in research community.

3.3 Forming Limit Diagram (FLD)

The usual method, Nakazima method, for determining FLD is to use a hemispherical punch (Limiting Dome Height – LDH test) with samples of different geometries to obtain various major and minor strain values at necking and/or facture [1]. The Marciniak test, as another test method for determination of FLD, provides in-plane stretching without the influence of friction by forming a sheet sample mated with a carrier blank and clamped at the binder. In a previous study it is shown that the measured out of plane forming limits were larger than those of in-plane stretching [3]. However, as reported by Lepping et al [4] and Abspoel et al [5], the non-linear strain path due to the biaxial pre-strain caused by localized initial stretching around the pole of the hemispherical punch may cause a change in the shape of FLD.

The conventional method for determination of the FLD (Nakazima method) is time consuming and need several numbers of samples with different dimensions to cover
all loading path of the FLD. Moreover, the edge quality, friction and the off-centric initiation of necking is always an issue in FLD. To overcome the time and the cost issue, a methodology is suggested and used by Li et al. [6] where the forming limit diagram is determined using only three points namely: a) uniaxial tension, b) plane strain, c) biaxial tension. Li and colleagues determined the strain values at the onset of necking using the DIC method. They used the LDH test for determination of the strain forming limits along the equi-biaxial and plane strain paths and the strain limit in uniaxial tension was measured from tensile test [6]. In order to eliminate the off-centric initiation of localization caused by friction and ensures strain localization at pole in the Nakazima testing, Kardogan et al. [7] suggested the use of a thick layer of flexible and durable polyurethane disc.

In the present paper, the authors propose a new and simplified approach for experimentally determination of FLD and reducing the cost and efforts to run the test. Using this new method, the flow stress data and the FLD can be determined simultaneously. In this method, the FLD is determined using only three points similar to what is suggested by Li et al. [6]. Two tests (LDH and VPB tests) are conducted for determination the strain values at fracture for plane strain and equi-biaxial loading state and the major and minor strain at fracture for uniaxial loading state is determined using the formula suggested by Abspoel et al. [8]:

\[
\varepsilon_1 = 1 + 0.797r^{0.701} \left( \frac{0.0626 A_{\beta 0}^{0.567} + (t-1)(0.12 - 0.0024 A_{\beta 0})}{\sqrt{(1 + (0.979r^{0.701})^2)}} \right)
\]

\[
\varepsilon_2 = -\left( \frac{0.0626 A_{\beta 0}^{0.567} + (t-1)(0.12 - 0.0024 A_{\beta 0})0.797r^{0.701}}{\sqrt{(1 + (0.979r^{0.701})^2)}} \right)
\]

Where \( r \) is the Lankford value, \( A_{\beta 0} \) is total elongation in tensile test, and \( t \) is the initial sheet thickness. The analysis of the tensile specimen using DIC during the tensile test shows the strain values around the localize necking location is smaller than what is obtained from the out-of-plane uniaxial Nakazima test. However, this issue is not reported by Li et al. [6] where they used tensile test to determine the major and minor strain at necking for uniaxial loading state.

The DIC system is used to measure the strains near the fracture point in LDH and VPB test. There are two advantages for determination the strain values in equibiaxial loading state using VPB test. First, the flow stress data can also be determined; second, there is no friction issue and concern about obtaining the fracture at the pole
any more. However, these issues still remain when determining the strain at fracture for plane strain loading state using LDH test. The proposed methodology is used for 0.96mm thick DP600 at IFU- Stuttgart University and the result is compared with FLC obtained from conventional Nakazima test, Fig 9. The calculated \( r \), and \( A_{80} \) for this material are 0.806 and 20\%, respectively.

![FLD for 0.96mm DP600 determined using conventional Nakajima test and proposed 3 point method](image)

**Figure 9:** FLD for 0.96mm DP980 determined using conventional Nakajima test and proposed 3 point method

As shown in Figure 9, the FLD determined using the methodology proposed in this paper is in a good agreement with the FLC determined using conventional Nakazima test. The strain values in equi-biaxial and plane strain loading state is quite match in both test. However, the strain value obtained from the formula proposed by Abspoel is about 5\% larger than what is obtained from the Nakazima test.

A similar procedure is repeated for 1.04mm AA6014 and the FLD is created using the three points as shown in Fig 10. The calculated \( r \), and \( A_{80} \) for this material are 0.68 and 25\%, respectively. The point for equi-biaxial and plane strain is in a good agreement with the conventional FLD curve. However, the point for the uniaxial tensile shows much larger strain than what is obtained from the conventional FLD test. As mentioned before, the major and minor strains for tensile test are calculated using the formulation by Abspoel, et al, [8] and this formula is developed based on a study for steels. Therefore, this can be the reason for the inaccurate calculation of the strains in uniaxial loading state for aluminum. So, some modification of the formula is required.
to be able to use it for aluminum. Additional studies are needed to establish the method to obtain the FLD, using 3 data points only.

**Figure 10:** FLD for 1.04mm Al 6014 using conventional Nakajima test and the proposed 3 point method

4. Lubrication and Coefficient of Friction (COF)

The development of new materials requires the use of new lubricants. With appropriate lubrication, failures associated with wrinkling or premature fracture can be reduced or even avoided. Furthermore, for a given die material and coating, appropriate lubricant helps to reduce die wear in large volume production. A “good” lubricant should provide, at an acceptable cost, minimum friction, or COF, reduce die wear, prevent corrosion, and easily removable from the stamped part.

4.1 Temperatures and pressures at die /sheet interface

Forming of AHSS generates higher contact pressures and temperatures due to higher strength and higher strain hardening, compared to conventional steels. Temperatures
and pressures at the interface affect the performance of lubricants. Therefore, lubricants for forming AHSS must contain high pressure and high temperature additives that are activated during extreme forming conditions and enhance the lubricant performance. These lubricants must also act as a coolant and remove the heat generated from cold working and friction at the interface, and be a thermal barrier to avoid excessive heat transfer to the tools from the part, [1]. As an example, Figure 11 shows the temperatures obtained from the simulation of a 55mm deep drawn 1.2mm thick DP980. It is seen that the temperature rise reached about 200 °C in some locations of the part. PAMSTAMP software is used for simulations. This temperature rise is only due to plastic deformation of the material and the effect of the friction is not considered in the simulation. Considering the friction, the temperature will be higher than this value. Also, 250KN blank holder force was used to avoid wrinkles and this high blank holder force provides high stress distribution on the part. Therefore, the lubricant used to form these high strength materials should have excellent performance in high temperature and pressure. During lubricant selection, it should be considered that there is always one lubricant better than the other one for a particular operation under given conditions.

Figure 11: Prediction of the temperature rise during the deep drawing of 1.2mm DP980 (part size is about 470mm x 300 mm)

4.2 Evaluation of lubricants using the Cup Draw Test (CDT)

There are many different laboratory tests that can be run to evaluate different lubricants. However, most of these laboratory tests such as Twist Compression Test (TCT) or Strip Drawing Test (SDT), do not emulate the conditions that exist in practical
stamping operations [1]. The Cup Drawing Test (CDT) is used at CPF to evaluate different lubricants. Fig. 12 shows the schematic of CDT.

![Figure 12: Schematic of the cup drawing test (CDT)](image)

As shown in Fig 12 and 13, the blank size is selected in a way that for a given blank holder force some flange left around the cup after drawing up to 80mm punch stroke. Measurement of the flange draw-in length is an indication of the lubrication performance. The larger is the draw-in length, or the smaller is the perimeter of the remaining flange after cup drawing, the better (lower COF) is the lubricant for a given Blank Holder Force. Also, an approximate COF for each lubricant is determined inversely through FE simulation. The advantage of the CDT compared to other laboratory tests is that in the CDT the experiment is carried out under conditions similar to real stamping. The effect of the pressure and the temperature due to the plastic deformation as well as the sliding of the material into the die cavity in the CDT can represent the similar conditions happening in other sheet metal stamping processes. Therefore, CDT is found to be more reliable in evaluating and ranking lubricants.

In a recent study conducted at the CPF, ten lubricants including a dry lubricant, from different suppliers are compared using CDT to evaluate the lubrication performance and select the best lubricant for forming the AHSS materials. Two different materials 1.2mm DP980 and 1.3mm DP590 are used in the study, Figure 14. Several FE simulations of cup drawing process using the same geometry are also conducted by using different COF. Flange perimeter is measured from the experiments and the average of the flange perimeter for each lubricant is compared with the simulations. The COF used in the simulation, which provides the same flange perimeter with experiment, is considered as the COF for that lubricant. It should be noted that the COF is not only dependent on the lubricant but also on other forming parameters such as the interface temperature, and pressure, and the ram speed.
Figure 13: Formed cup in CDT and evaluation of the lubricant by measuring the perimeter

Figure 14 illustrates, as an example, the results of CDT in evaluating four different thixotropic lubricants that become less viscous under shear loading, or deformation. The results are compared with the best liquid lubricant that was selected in a previous study. It is seen that three of four tested thixotropic lubricants performed better than the “best” liquid lubricant.

Figure 14: Comparison of flange perimeter in CDT. X, Y, Z, and CF are thixotropic lubricants and B is the liquid lubricant
5. Use of Servo Press in Forming AHSS and Al Alloys

Servo-drive presses offer a higher productivity, i.e. strokes per minute, compared to similar size and capacity mechanical presses. In addition, the servo drive offers a) infinitely variable ram speed, within the limits of the dynamics of a given press, and b) dwell and restriking at the Bottom Dead Center (BDC), as seen in Figure 15.

Thus, in addition to offering a productivity increase servo press has the potential to improve part quality, i.e. part definition and reduced springback, especially when the adjustable slide motion is used in combination with a CNC hydraulic cushion.

Figure 15: Capability of infinitely variable and adjustable ram speed and dwell at Bottom Dead Center (BDC) in servo press

In summary, the main advantages of electro-mechanical servo drive presses include:

a) Precise ram position and velocity control, during the stroke which allows for (i) easier set up, (ii) preventing noise and shock when contacting the workpiece and during upstroke, (iii) improved formability for reducing the ram velocity during part deformation, i.e. drawing or blanking, (IV) reduction of reverse tonnage in blanking.
b) Adjustable stroke length (TDC-BDC). (This provides flexibility so that in the same press drawing and blanking can be conducted with increased stroke/min. Also the press can be run in pendulum motion mode).

c) Ram position/velocity can be synchronized with automatic (or robotic) part transfer. Thus, strokes/min can be increased.

d) Part/min produced is larger than in mechanical presses of comparable capacity because of rapid down and up stroke, while reducing ram speed during deformation.

e) Savings in energy, since there is no flywheel which is driven continuously.

f) Possibility of dwell anywhere in the stroke and mainly at BDC and re-striking capability (this allows reduction in and control of springback).

g) Max motor torque (press load) may be available during the entire stroke, depending on press linkage design.

At CPF, a study is ongoing to evaluate the formability of the AHSS and Al 5182-O using a nonsymmetrical die set and 300 ton Aida servo press with a CNC hydraulic cushion. The effect of the variable forming speed, variable blank holder force, and cushion pre-acceleration on formability of the material and reducing the possibility of the fracture and wrinkle are investigated. Figure 16 shows the press output for the blank holder force and ram speed used in the tests.

![Figure 16: Variable ram speed and blank holder force used in forming of AHSS and AL5182-O using 300 ton AIDA servo press](image)
Figure 17 illustrates the schematic of the tooling built to investigate the formability of AHSS and Al alloys using a servo press. In the design phase, several "virtual tryouts" were conducted using the FE software PAMSTAMP for simulations.

![Schematic of tooling](image)

In order to conduct the simulations the flow stress curve was obtained from the bulge test, Figure 8, and the COF was determined using the combination of simulation and the CDT, Figure 12.

### 5.1 Forming of Al 5182-0 in the Servo Press

Figure 18 shows the actual formed part at 75 mm draw depth and the simulation results of drawing Al 5182-0. The thinning measurement and prediction in the drawn part at the critical corner area is shown in Figure 19. This figure also illustrates how the COF and the source of the flow stress data (tensile or bulge) affect the simulation results. It is seen that the simulation results, obtained using the bulge test data are closer to experimental thinning measurements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concave side radius</td>
<td>( R_1 )</td>
<td>601.6mm</td>
</tr>
<tr>
<td>Convex side radius</td>
<td>( R_2 )</td>
<td>598.4mm</td>
</tr>
<tr>
<td>Convex side radius</td>
<td>( R_3 )</td>
<td>51.6mm</td>
</tr>
<tr>
<td>Cavity corner radii</td>
<td>( R_4 )</td>
<td>56.6mm</td>
</tr>
<tr>
<td></td>
<td>( R_5 )</td>
<td>61.6mm</td>
</tr>
<tr>
<td></td>
<td>( R_6 )</td>
<td>66.6mm</td>
</tr>
<tr>
<td>Die-corner radius</td>
<td>( R_7 )</td>
<td>10mm</td>
</tr>
<tr>
<td>Punch-corner radius</td>
<td>( R_8 )</td>
<td>10mm</td>
</tr>
</tbody>
</table>

![Die set used for deep drawing in the 300 ton Aida servo press (originally designed to form AHSS) front and cross-section view. The die is built by Shiloh Inc.](image)
Figure 18: Aluminum panel formed by 300 Ton servo drive press and simulation results of the same operation

Figure 19: Comparison of measured and predicted thinning at the critical corner of the drawn part (Material: Al 5182-O, thickness = 1.2 mm, BHF = 150 ton, COF = 0.1 and 0.12, Draw Depth = 75 mm, Ram speed = 310 to 0 mm/s)

By comparing the measured load-stroke curve with the predicted one, it is possible to "adjust" the value of the COF, use in the simulations. Thus, a more realistic COF, which is valid for actual forming, can be estimated, Table 1.
Table 1: Comparison of the maximum ram force value obtained from the experiment with those predicted by FE simulation with two different COF.

<table>
<thead>
<tr>
<th>Material</th>
<th>Drawing Depth (mm)</th>
<th>Max Total Ram Force (KN)</th>
<th>Max Total Ram Force, simulation with COF=0.09 (KN)</th>
<th>Max Total Ram Force, simulation with COF=0.12 (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP590</td>
<td>1.3mm</td>
<td>70</td>
<td>737</td>
<td>677</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>724</td>
</tr>
<tr>
<td>CP800</td>
<td>1.4mm</td>
<td>50</td>
<td>838</td>
<td>792</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>842</td>
</tr>
<tr>
<td>DP980</td>
<td>1.2mm</td>
<td>55</td>
<td>874</td>
<td>815</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>871</td>
</tr>
<tr>
<td>TWIP900</td>
<td>1.2mm</td>
<td>70</td>
<td>719</td>
<td>652</td>
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<td></td>
<td></td>
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<td></td>
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<td>794</td>
</tr>
</tbody>
</table>

5.2 Forming of AHSS in a Servo Press

FE simulations are conducted to investigate the ability of predicting the tool and specimen temperatures, as well as the thinning during the forming process for several AHSS, Table 1. As an example, preliminary results given in Figure 20, show a temperature increase up to 200°C for DP980 with 1.2mm thickness, around the corner of the formed part after 55mm punch stroke (draw depth). The predicted temperature increases may not be quite accurate since the thermal parameters are based on the low carbon steel and tool steel parameter for blank and tools respectively. Also the temperature due to the friction is also not considered in this simulation and the temperature rise is only due to the deformation of the material.

Figure 20: (a) Thinning and (b) Temperature predictions for 55mm deep drawn DP980 sheet with 1.2mm thickness (PAMSTAMP)


6. FE simulations of sheet metal forming

Finite Element (FE) simulation is widely used in sheet metal forming industries to predict the difficulties and issues during the manufacturing of the part from die design to forming process. The FE simulation is used before manufacturing a real part in order to reduce the cost and the time for trial and error. However, the accuracy of the predicted results is highly dependent on the data inputted to the model which includes: material properties, Yield criterion, extrapolation method, friction model, and the mesh size and type.

6.1 Material properties and friction model for FE simulation input

As discussed before, flow stress data (hardening curve) is one of the most important material properties for the simulation of sheet metal forming. The prediction of the flow of the material, the thickness distribution, forming load are directly related to the hardening curve inputted into the model. Using tensile data cannot provide accurate flow stress data for high strain values and extrapolation using K and n can cause inaccuracies. In most studies, the flow stress data are represent by K and n values that are considered to be constant. However, for some materials the n value may not be constant. The use of the new proposed combined method for flow stress data can reduce the inaccuracy of the extrapolation. Young’s modulus is the other important material property that can significantly affect the simulation results especially in terms of prediction of springback. In most simulations the Young’s modulus is considered as a constant value while previous studies has shown that for some materials the E-modulus is changed by strain. FE model with variable E-modulus can increase the accuracy of the results. However, it should be noted that all experimental data for E-modulus versus strain are from tensile test and are for relatively small strain range. There is same issue for R-values and there is no commercial FE software that can handle variable R-values versus strain through the simulation steps.

The friction model used in the simulation of sheet metal forming is the Coulomb model. As discussed earlier, the temperature and the pressure on the sheet metal is changing through the process. Change in these parameters can affect the lubrication performance and friction. However, in most FE codes the COF is considered as a constant number. At CPF a study is ongoing to determine the temperature and the pressure on the sheet surface in cup drawing simulation. This information is going to be compared with TCT results (experiment and simulations) and the effect of the temperature on the COF can be determined. These data may be used later in some
FE software to be able to conduct deep drawing simulation with a friction model as a function of pressure and temperature.

### 6.2 Element size and type

Preliminary results of a study ongoing in the CPF show that beside the material properties and the simulation inputs, the element size and type used in the model can affect the simulation results significantly. All simulations discussed in this study are done using PAMSTAMP. In PAMSTAMP the blank is defined as shell element. Therefore, there is no element in the thickness direction of the sheet. The shell element is developed for simulation of thin parts like a sheet where the dimension in one direction is smaller than the other two directions. Due to the less number of the elements when the shell element is used, the simulation time will decrease. It is recommended by PAMSTAMP manual that four node rectangular elements provide more accurate result than three node triangle elements. Therefore, it can be said that for simulation of sheet metal forming, four node rectangular shell element can be appropriate as element type. Beside the element type, the element size is also important. In most current FE software packages there is an option for element refinement process during the deformation. This option allows to start the simulation with relatively large initial element size and then the model automatically refines the element (that of the blank), where and when it is required. In the PAMSTAMP the program performs a one-level refinement when this element is cut into four other elements, figure 21.

![Figure 21: The methodology PAMSTAMP is using to automatically refine the elements [13]](image)

Two criteria, schematically shown in figure 22, can be used to determine whether refinement should be used or not namely: a) angle criterion and b) geometrical criterion. In angle criterion the solver refines an element when the variation of the angle between the initial and that of one of its neighbors exceeds a limit angle which is 10° in default setting. The angle criterion is useful for detection of the wrinkle. In the
geometrical criterion the solver adapts the density of the element to the local curvature of the tools close to the blank. The element adaptive process initiates the blank refinement before errors due to a too coarse mesh appear in the simulation and provides a more accurate calculation of the stress field.

![Angle criterion](image)

![Geometrical criterion](image)

**Figure 22:** Two different criteria PAMSTAMP is considering to determine where and when the element has to be refined [13]

However, as mentioned earlier, the initial element size can influence the accuracy of the simulation results even if the automatic element adoptive option is used in the simulation. Therefore, a study is ongoing here at the CPF to investigate the effect of the initial element size on the simulation of deep drawing process. Also, this is desirable to develop a standard procedure for determining the initial element size for simulation of deep drawing process using shell element in PAMSTAMP. When the automatic element refinement option is selected, the program calculates the final element size based on the minimum sliding radius (the smallest radius where sliding can occur) and the following formula:

\[
\text{Final element size after refinement} = d \leq \frac{1}{4} (R + \frac{1}{2} \text{ thickness})
\]

Where, \( R \) is the minimal sliding radius. If the initial element size of the blank is smaller than the \( d \) which is calculated above, the element refinement is not refining the element anymore. Simulations of cup drawing process of 1.2mm DP980 material are conducted using the geometry shown in figure 12. The die corner radius is 16mm (minimal sliding radius). The calculated final element size after refinement is 4.15mm and if the initial element size is smaller than 4mm the element adaptive system is not refining the elements any more. Results show that using relatively small element size...
not only increases the simulation time but also can reduce the accuracy of the simulation results. Figure 23 shows the thinning distribution along the curvilinear length of the cup for different initial element size and compared with the experimental result. As shown in this figure, result of simulation with 10mm element size is more accurately following the trend of the thinning distribution compared to the experiment. Also, for smaller element size (1mm and 3mm) some fluctuations are observed in area around the punch corner radius (C-D). These fluctuations reduce the accuracy of the simulation results. Moreover, the location of the predicted maximum thinning is around punch corner radius when mesh size 1mm is used while in the experiment and also two other simulations with element size 3mm and 10mm, the location of the maximum thinning is on the wall of the cup.

![Figure 23: Comparison of thinning prediction for different element size with experimental result](image)
7. Conclusions and Future Work

To reduce weight, new materials with high strength to weight ratio, are used, provided they can be processed at an acceptable cost. Virtual stamping and the actual production of parts require accurate determination of material properties (flow stress, E-modulus, formability), the Coefficient of Friction, and the appropriate FE model (mesh size, simulation parameters). In general, the following assumptions are made in die and process design, especially in the simulation stage:

a) The material properties are given, based on tensile test standards. Thus, in many cases yield stress, ultimate tensile strength and total elongation that are obtained from a uniaxial tensile test are provided by the material supplier. This information is not sufficient to develop a correct flow stress curve. Even, when the true stress-true strain curve is available, from the tensile test, this information is curve fitted to an exponential form, \( \sigma = K\varepsilon^n \) to obtain the K and n values. Thus, the information is extrapolated with unknown approximations.

It is more appropriate to use the flow stress curve that is obtained from the combination of uniaxial tensile and biaxial bulge test, as discussed in Section 2.

b) n-value. It is generally assumed that the “n” values is a constant. Studies have shown that this is not the case, especially at large strains for some AHSS. Thus, in the future it may be useful to consider n as a function of strain, at least for most AHSS.

c) Friction and lubrication. The experimental result of CDT show that the lubricants can be evaluated using this test. CDT is providing the forming condition (pressure and temperature beside the plastic deformation of the material) similar to what is happening in most sheet metal forming processes. Therefore the result of this test can be more reliable than other laboratory tests. Coefficient of friction can also be determined inversely using FE simulation. However, it is known that in reality the friction between the sheet surface and the tools is more complicated and dependent on the pressure and the temperature of the different locations.

d) FE simulations and element size. Preliminary result of the ongoing project is showing that reducing the mesh size is not always providing better prediction results. Comparison of the simulation results with experiment for cup drawing test is showing that using the element size larger than the value determined by equation (4) and selecting the element adoptive option in the simulation provides more accurate simulation results. This study is still ongoing and the purpose is providing a guideline to know what element type and size can provide reliable simulation results.
Literature


