Temperature Increase in Forming of Advanced High-Strength Steels Effect of Ram Speed Using a Servodrive Press

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In forming of advanced high-strength steel (AHSS), the temperature increase at die/sheet interface affects the performance of lubricants and die wear. This study demonstrates that finite-element (FE) analysis, using commercially available software, can be used to estimate temperature increase in single as well as in multiple stroke operations. To obtain a reliable numerical process design, the knowledge of the thermal and mechanical properties of the sheet as well as the tools is essential. Using U-channel drawing the thermomechanical FE model has been validated by comparing predictions with experimental results. The effect of ram speed and stroking rate (stroke per minute (SPM)) upon temperature increase in real productionlike operation have been investigated. Deep drawing of CP800 and DP590 sheets in a servodrive press, using an industrial scale die, has been studied. Thinning distribution and temperatures in the drawn part have been investigated in single and multiple forming operations. It is found that temperatures may reach several 100 deg and affect the coefficient of friction (COF). The values of COF under productionlike conditions were compared to that obtained from laboratory experiments. This study illustrates that in forming AHSS, (a) the temperature increase at the die/sheet interface is relatively high and should be considered in process design stage, and (b) the lubricant performance is significantly affected by the ram speed and sheet/die interface temperature during deformation.

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1 Introduction
Light-weight design has become essential for automotive industry due to its considerable economic and ecological benefits (i.e., higher fuel economy and lower emission). High-strength and lightweight materials are introduced for a wide range of body panels and structural parts. In addition to Al alloys, advanced and ultrahigh-strength steels are increasingly used in automotive manufacturing. Therefore, to minimize the part failure and tool wear, press speed during part deformation often needs to be reduced. Electromechanical servodrive presses provide precision ram position and velocity control during the stroke. This allows improvement of drawability by only reducing the ram velocity during the part deformation stage, without significantly reducing the production rate [1,2].

In sheet forming of AHSS, the heat generated due to friction and plastic deformation can reach up to about 100–200 °C depending on process type and speed [3,4]. As reported by Farren and Taylor [5], approximately 90% of the work done for the plastic deformation is converted into heat and the remaining 10% is used up in increasing the internal energy of the material [5]. For material with temperature dependent flow stress, temperature raise during the deformation can affect the stiffness of the material and lowering the flow stress data. This softening can increase the real area of contact resulting in higher adhesion. It has been reported that adhesion starts to rise at approximately 125–150 °C [6].

From the tribological point of view, temperature rise during the deformation can affect the properties of the lubricant and influence the lubrication performance. Organic based lubricants, which often used in sheet metal stamping, can be used below 250 °C without significant thermal degradation [7]. Therefore, it is important to accurately determine the fraction of deformation work which goes to increasing the temperature of the material during the sheet forming process. There are a few studies that investigated the temperature generation in forming of AHSS and aluminum alloys using numerical or experimental procedures [3,4,8,9]. Kim et al. [3], investigated the shear fracture at die corner radius in draw bending test of DP980 and they concluded that the deformation-induced heating, in the order of 75 °C, has a dominant effect on the occurrence of shear failure [8].

In order to determine the temperature, cost, and time could be greatly reduced by using computer simulations rather than running experiments with a try-out press in the die shop. FE simulations were used for temperature prediction in metal forming process [3,4,8,9].

In published literature, the temperature at the part/tool interface is predicted after a single forming operation. However, it is important to estimate how the temperature increases after several numbers of forming operations, especially in forming of AHSS materials. In the current study, first a simulation of U-channel drawing is conducted to validate the methodology and assumptions used in the thermomechanical simulation model, by comparing the predictions with experimental results available in the literature. Then, a similar thermomechanical FE model for deep drawing of industrial scale nonsymmetric panel is developed. The temperature rise in sheet and tools is determined for two different AHSS materials (1.4 mm CP800 and 1.4 mm DP590). The simulation results are validated with experimental results in terms of thinning distribution. Effect of COF and lubrication performance on temperature generation at tool/sheet interface is investigated. Simulations of multiforming operation of U-channel forming and deep drawing process were conducted to investigate the effect of the ram speed (SPM) on temperature rise at the tool surface after several consecutive forming operations.

2 Material Model and Element Type
In the present study, three different AHSS materials, complex phase grade steel CP800 (1.4 mm), and dual phase grade steels DP90 (1.4 mm), and DP780 (2.5 mm), are examined. Tensile properties for DP780 were obtained from literature [4], and for CP800 and DP590 tensile tests, in rolling direction, were conducted at Honda R&D Department of Honda America Raymond, OH. Hill 48 plasticity law with isotropic material model was used for simulating the plastic behavior of the sheet. The flow stress for CP800 and DP590 materials were obtained from the viscous pressure...
The sheet material was simulated using shell elements with five integration points through thickness direction. The initial element size was selected based on the minimum sliding radius in each die set. In simulations of deep drawing process “mesh refinement” option was activated as suggested by PAM-STAMP V15.1 manual.

It is known that the surface heat transfer coefficient (SHTC) is a function of gap and pressure between the sheet and the tool surfaces. However, due to simplicity, this parameter was considered as a constant value. In simulation of multifoming operations, the heat convection between the tool surface and the air, a factor that influences temperature reduction during the die opening and transformation stages, is also considered. The initial temperature of the sheet and the tools is neglected. The tools are simulated as surfaces (not volume) to reduce the simulation time. Six thermal points were located where severe deformation occurs. The elastic deflection of the tools is neglected. The tools are simulated as surfaces (not volume) to reduce the simulation time. Six thermal points were considered in the thickness direction for the tools. The prediction error due to use of surface element instead of solid element is not investigated in this study.

3 U-Channel Drawing

3.1 Simulation Setup and Validation of Thermomechanical FE Model. Three-dimensional coupled thermomechanical FE model is developed to analyze the U-channel forming of DP780 (2 mm). Figure 2 shows the geometrical parameters of the die and specimen. The commercial software PAM-STAMP-V15.1 with explicit solver was used. The die geometry and tooling setup is similar to what was used in experiments to be able to validate the accuracy of the simulation model and results by comparing with experimental results [4]. The model consists of die, punch, blankholder, ejector pin, and sheet. The punch was fixed in all three directions. Blankholder and die were fixed in X and Y directions and allowed to move in the Z direction which was considered as the forming direction. 27 kN constant force was applied on the blankholder and the ejector pin. The distance between the die and the blankholder was checked in several forming strokes to ensure

### Table 1 Mechanical properties of sheet materials used in this study. Data for DP780 is from Ref. [4].

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile test</th>
<th>Bulge test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yield stress (MPa)</td>
<td>Tensile stress (MPa)</td>
</tr>
<tr>
<td>DP780 (2 mm)</td>
<td>587</td>
<td>884</td>
</tr>
<tr>
<td>DP590 (1.4 mm)</td>
<td>355</td>
<td>600</td>
</tr>
<tr>
<td>CP800 (1.4 mm)</td>
<td>770</td>
<td>900</td>
</tr>
</tbody>
</table>

### Table 2 Thermal properties used in the thermomechanical FE simulation. Thermal properties for sheet are for low-carbon steel and are from previous publication by Pereira and Rolfe [4].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheet length</td>
<td>150</td>
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<tr>
<td>Sheet width</td>
<td>26</td>
</tr>
<tr>
<td>Sheet thickness</td>
<td>2</td>
</tr>
<tr>
<td>Corner radius</td>
<td>5</td>
</tr>
<tr>
<td>Corner radius</td>
<td>5</td>
</tr>
<tr>
<td>Punch width</td>
<td>30</td>
</tr>
<tr>
<td>Punch clearance</td>
<td>2.35</td>
</tr>
</tbody>
</table>

Fig. 1 Flow stress data for 1.4 mm CP800 and DP590 obtained from the VPB test.

Fig. 2 Schematic cross section of the simulation setup and the geometrical parameters used for simulation of U-channel forming [4].

This option allows the software to more accurately calculate the flow of the material by automatically reducing the element size at locations where severe deformation occurs. The elastic deflection of the tools is neglected. The tools are simulated as surfaces (not volume) to reduce the simulation time. Six thermal points were considered in the thickness direction for the tools. The prediction error due to use of surface element instead of solid element is not investigated in this study.
the closure of the blankholder. The die movement is specified by speed versus time curve. The same speed pattern used in the experiment was applied to the die representing the motion of the single-action mechanical press with 1 SPM ram speed [4]. Based on the geometry of the press, the crank rotational speed and the drawing depth used in the experiment, the deformation starts at about 8 mm/s and reduces to 0 mm/s at the end of 40 mm forming stroke. The total forming duration was about 9 s. The temperature at the die/sheet interface was predicted and compared with experimental results.

3.2 Results of U-Channel Drawing and Validation of Thermomechanical FE Model. Several assumptions were made in the simulations due to unavailability of the required data. These assumptions, discussed below, can limit the accuracy of the simulation results: (a) the accurate thermal properties of the sheet material used in this study were not available. So, the properties of low-carbon steel were used from literature; (b) the heat transfer coefficient which determines the amount of the heat transferred from sheet to the dies was considered as a constant value. However, as determined experimentally, this value is a function of the gap and pressure between the sheet and the die [9,11]; (c) the heat transfer from sheet to the dies was considered as a constant value. How- ever, the COF is not constant in all locations in the die during stamping.

Figure 4 shows the predicted maximum temperature generated at the die/sheet interface compared to the experimental results. Simulation results are in good agreement with experimental measurements from Ref. [4]. The maximum predicted temperature at the die/sheet interface goes up to about 45°C (25°C temperature rise) after about 3 s of drawing (about 22 mm drawing depth) and drops to about 33°C at the end of deformation. Similar trend was observed in experiments. The temperature rise in terms of value and trend follows the experimental measurement very well. Therefore, the prediction error as a result of using thermal properties of low-carbon steel instead of the real values for the specific sheet material used in the experiment can be considered to be negligible. Also, it can be concluded that the methodology and the boundary conditions used to develop the thermomechanical FE models in this study can predict the temperatures close to that encountered in the real stamping operations.

Some inconsistency of the simulation results compared to the experiment can be observed at about 2–3 s after the deformation starts. Since the temperature and pressure can affect the lubrica- tion condition and COF, assuming a constant value of COF in simulation causes some errors in predictions. However, due to unavailability of data for variable COF in function of pressure and temperature for the lubricant used in the study, it was not possible to use a variable COF in the simulations.

4 Deep Drawing of Nonsymmetrical Industrial Size Panel

4.1 Experimental Procedure. Figure 4 shows a schematic of the die geometry used for deep drawing process in this study. The die was manufactured by SHILOH Industries, Valley City, OH. 1.4 mm CP800 and DP590 sheet materials were used in the experiments. The tensile test and the bulge test results showed that DP590 is more formable than CP800, by comparing the uniform elongation and bulge height. Therefore, the total drawing depths 70 mm and 48 mm were selected for DP590 and CP800, respectively. Rectangular sheets (600×395 mm for CP800, and 640×435 mm for DP590) were used. In case of DP590, the corners of the sheet were chamfered by 100×75 mm to reduce the possibility of wrinkle and improve the drawing process.

The sheets samples were cleaned by acetone and then lubri- cated in both sides. Cup drawing test (CDT) as a regular lubrication test in sheet metal stamping [3,12] was used for the evaluation of lubricants. Ten different lubricants suggested by lubricant companies, for deep drawing of AHSS, were tested. In cup drawing lubrication test, sheets are lubricated on both sides and then formed up to a predefined drawing depth using a constant blankholder force. The tests were performed at about 30 mm/s ram speed using 160-ton hydraulic press. Then, the flange perimeter of the cups was measured and the lubricants were ranked based on the length of the flange perimeter. The flange length, as a function of lubrication performance, is smaller when the cup draw-in is more and it is an indication of better lubrication performance. The selected lubricant used in this study, polymer synthetic, was provided by IRMCO Company, Evanston, IL, and was one of the best ranked lubricants from the CDTs.

A 300-ton Aida servodrive press with 25-ton servohydraulic cushion was used. This press provides accurate control of ram displacement/speed and blankholder force during the deformation process. The press speed, at the stroke position when the punch touched the sheet, was about 75 mm/s. A constant blankholder force was used. Preliminary simulation results showed that 200 kN and 250 kN constant blankholder forces were sufficient to maintain closure of the blankholder and avoid creation of wrinkles for the sheet size used to form DP590 and CP800, respectively. Three samples from each material were used in the tests. However, due to the difficulty of cutting the materials for thickness measurement, only two samples from each material were measured.

4.2 FE Model of Deep Drawing Process and Prediction of Thinning. Three-dimensional thermomechanical simulation model of deep drawing process for CP800 and DP590 with
1.4 mm thickness was developed using the die geometry shown in Fig. 4. The model consists of die, punch, blankholder, pad, and sheet. The boundary conditions are set similar to what was used in the experiments. The punch was fixed in all three directions. Blankholder, pad, and die were fixed in X and Y directions and allowed to move in the axial Z direction (forming direction). A constant 250 and 200 kN blankholder force were applied on the opposite direction of the die movement for CP800 and DP590, respectively. A 2 kN force was also applied on the pad to avoid the separation of the sheet from the top of the punch. The tools were modeled using surface elements and considered as rigid body. Similar thermal and mechanical properties as described in Sec. 2 for the tools and sheets are used.

As mentioned in Sec. 4.1, due to the different formability of DP590 and CP800, different sheet sizes and drawing depths were used for each of these materials in the experiments. Therefore, a simulation model, with drawing depth and blankholder force according to the experimental setup, is developed for each material.

In order to be able to investigate the effect of the material properties on temperature rise at the tool/sheet interface, simulation with similar forming conditions and sheet dimensions used for CP800 was also conducted for DP590. In this way, the only difference that provides different temperature predictions in the simulation models is the shear material properties.

In order to determine the COF from the CDT test, several simulations of cup drawing process with different COF values were conducted with similar boundary conditions used in the lubrication evaluation tests. The COF value which provides the similar flange length as measured from the experiment is selected as the COF for that lubricant, COF = 0.08. Then, this calculated COF value is used as initial COF in simulations of deep drawing process. The predicted load–stroke curves from the simulations with COF = 0.08 were compared with that obtained from the experiments. It was observed that the predicted load–stroke curves were slightly lower than experimental results. Therefore, the initial COF (0.08) was modified and increased to the value (COF = 0.12) that the predicted load–stroke curves match with experiments.

4.3 Results of Deep Drawing Process Using Nonsymmetrical Die Geometry and Comparison With Experimental Results. Similar assumptions, mentioned in Sec. 3.2, are also considered for simulations of deep drawing process. However, as discussed in Sec. 3.2, these assumptions are not significantly affecting the accuracy of simulation results in terms of temperature prediction. Comparison of simulation results with experimental measurements in terms of both temperature prediction and thinning distribution shows that the FE model and the boundary conditions used in the current study are reasonably reliable.

4.3.1 Prediction of Thinning Distribution and Validation of the FE Model. Thinning distribution along the curvilinear length at the corner of the panel where the maximum thinning is predicted in simulation, Fig. 5, is compared with experimental measurements, Figs. 6 and 7 for CP800 and DP590, respectively. For CP800, the maximum predicted thinning on the part is about 13%, Fig. 5. However, the maximum thinning value calculated along the curvilinear line is about 9%, Fig. 6. The reason is that the curvilinear line where the thinning values are measured in experimental samples is not passing through the element which shows the maximum thinning in simulation. For CP800, results showed the predicted thinning is in the same range of the thinning measurement from the experiments except at location number 4. The nominal sheet thickness was about 1.4 mm and the real initial thickness was not measured before the test. A small difference between the nominal and real thickness (even about 0.05 mm) for a sheet in range of 1.4 mm thickness cause about 3% different in thinning measurement. The differences between the prediction and experimental thinning measurements in this study are less than 3%.

Similar results are illustrated in Fig. 7 for DP590 formed up to 70 mm drawing depth using 200 kN blankholder force. For this material also, the maximum difference between the predicted thinning value and the experimental measurement is about 4%.

4.3.2 Effect of the COF on Temperature Rise at Die/Sheet Interface. Once the accuracy of the simulation results are validated by comparing the thinning predictions with experimental measurements, temperature rise at the tool/sheet interface is investigated for CP800 and DP590 used in this study. The COF used in the deep drawing simulation is initially determined by CDT and then modified by comparing the load–stroke curves of the simulations and experiments, as described in Secs. 4.1 and 4.2. The reason for calculating different COF in deep drawing process...
shown in Fig. 4).

Temperature rise at the die/sheet interface is predicted for two different COF values (0.08 and 0.12) during the forming of 1.4 CP800 up to 48 mm. Temperature rise versus stroke is shown in Fig. 8. As expected, the maximum temperature for lower COF is lower. Changing the COF from 0.08 to 0.12 increases the maximum temperature at the die/sheet interface at 48 mm stroke from about 80 °C to 91 °C. Therefore, using accurate COF is necessary for accurate prediction of temperature in the simulation of sheet metal stamping.

5 Multistroke Forming Operations

5.1 Simulation Setup. Similar methodology used for the single forming operation was used to simulate the multiforming operation of the U-channel-forming and the deep drawing processes. The temperature rise at the die/sheet interface was predicted compared to the CDT can be described due to different pressures and temperatures at die/sheet interface in these two different forming processes. The CDT was performed at about 30 mm/s ram speed but the deep drawing process was conducted at about 75 mm/s. In the deep drawing process, the forming speed is about two times faster and the die corner radius is smaller (10 mm compared to 16 mm) compared to the CDT. Smaller die corner radius and more complexity of the die cavity compared to the cup drawing cause higher strains at the part and consequently increase the deformation-induced heating. Also, the faster ram speed in deep drawing experiments reduces the time of heat distribute through the tools by conduction. So, the temperature at the tool/sheet interface was higher in deep drawing process compared to CDT. This higher temperature can affect the lubrication performance and increase the COF. Also, the different pressure between the tools and the sheet in the CDT and the deep drawing operations can be another reason for different COF values. As reported in several previous publications [7,13,14], assuming a constant COF for whole model is not accurate. FE model with variable COF as a function of temperature, and pressure can increase the accuracy of the simulation results. However, variable COF values as functions of pressure and temperature are not available at this moment.

The FE simulation of deep drawing process for DP590 with the conditions used in the experiment (640 × 435 mm rectangular sheet, 200 kN blankholder force, and 70 mm drawing depth) is also conducted, to predict the temperature in the part and tool/sheet interface at similar conditions to what the material was tested. The location of the maximum temperature at 70 mm stroke was in the same location shown in Fig. 9, but the value reached up to about 130 °C. The maximum temperature calculated at the die/sheet interface at this stroke was about 110 °C.

Current metal manufacturers and automotive companies are investigating the development and production of materials with tensile strength of about 1500 MPa. Based on the simulation results presented in this study, the temperature at the part for these ultrahigh-strength materials can reach up to 200 °C. This high temperature can affect the lubrication performance, the material properties, and the surface quality of the part and the tooling.
immediately after when the deformation stage was finished and also before starting the next steps.

For U-channel drawing, two different forming speeds, 5 SPM and 30 SPM were considered. The ram (punch) speed during deformation was calculated using the well-known equations for slider-crank mechanism of the press [14,15].

The information, used in the simulation of multistroke forming operations of U-channel drawing was as follows:

- For press speed at 5 SPM, the ram speed at contact was 41 mm/s, the duration of forming was 2 s, and the transfer time between two strokes was 10 s.
- For press speed at 30 SPM, the corresponding values were 250 mm/s (ram speed at contact), 0.32 s (duration of forming), and 2 s (transfer time between two consecutive strokes).

The material data for 1.4 mm CP800 is only used in simulation of multistroke deep drawing operations. Crank diameter of the servopress used in the experiment, 400 mm, was utilized to create the ram speed versus stroke curve. As a particular characteristic of the servodrive presses, the selected ram speed versus stroke, Fig. 10, allows the press to move at 6 SPM before and after touching the material while during the material deformation the ram speed remains constant, 75 mm/s. The total duration from the start of one forming operation to the next was considered about 10 s (6 SPM). The forming duration was about 0.64 s (75 mm/s and 48 mm drawing depth) and 9.36 s was considered for die opening and part transformation.

5.2 Results and Discussion. Servodrive presses, compared to mechanical presses of similar capacity, can be run 50–100% faster, in terms of SPM. However, it is not completely clear how temperature at the tool sheet interface increases at multiforming steps at different forming speeds. Therefore, in the current study the simulation of multiforming operations of U-channel drawing and deep drawing were investigated as two examples.

Figure 11 shows the increase of maximum temperature predicted at die/sheet interface for 2 mm DP780 after several operations of U-channel drawing with two different forming speed (5 and 30 SPM). At 5 SPM ram speed, the maximum temperature at die/sheet interface increased from 41 °C to 46 °C after eight operations. At 30 SPM, maximum temperature increased from 100 °C to 117 °C after nine operations. However, the temperature rise at die/sheet interface does not increase significantly (less than 1 °C) after nine operations and reach almost steady-state condition. As expected, using faster forming speed and transfer time, the temperature at the die/sheet increased significantly. Faster forming operation reduces the time of heat transfer from the tools surface into the air, and therefore, the temperature rise after several operations was more significant when using a faster ram speed.

Figure 12 shows the max temperature rise at die/sheet interface for several forming operations of deep drawing process for CP800 at 6 SPM production rate. The maximum temperature increased 6 °C after seven forming operations. The temperature rise from the sixth to the seventh operation is about 2 °C and the temperature rise does not reach steady-state condition after seven operations. However, the main objective of this study is to show how temperature rises during the deformation of AHSS. The calculation of the maximum temperature when steady-state condition reached is out of the scope of this study. Therefore, to save computation time, the model was developed to predict the temperature only up to seven strokes.

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Below is a summary of the results obtained from the simulation of both U-channel forming and deep drawing:

(a) the die/sheet interface temperature increases with increasing deformation speed, as indicated by SPM
(b) the die surface temperature continues to increase slightly during multiple successive forming operations, until a near steady-state surface temperature is reached

6 Summary and Conclusions

The objective of the study, discussed in this paper, was to understand and explain how die/sheet interface temperatures can be predicted for given forming conditions. The knowledge of the interface temperatures are expected to help in evaluating lubricant performance and, possibly, in understanding die wear and galling issues.

Two forming examples were studied: (1) U-channel drawing of 2 mm thick DP780 and (2) deep drawing of DP590 (1.4 mm) and CP800 (1.4 mm) in a nearly rectangular die. FE models were developed for both applications to predict die/sheet interface temperatures. In case of U-channel drawing, the predictions were compared with experimental data from the literature and reasonable agreement between predictions and measurements were found. In case of deep drawing, the thinning in the part and temperatures were estimated. The effect of press speed and temperatures upon friction was discussed. Forming in single as well as in multiple-consecutive press strokes was considered.

This study illustrated that it is possible to estimate temperatures at the die/sheet interface, using FE simulation. The temperature prediction and thinning distribution were in good agreement with experimental results. In U-channel drawing, the temperature increases with increasing forming stroke and then decreases toward the bottom dead center. The location where the temperature at the tool/sheet interface starts to decrease is dependent of the geometry and the forming speed. On the other hand, in deep drawing operations, the temperature in the part as well as the die/sheet interface keeps increasing with forming stroke. The COF used in the FE simulation can significantly affect the prediction of the temperature. Therefore, for accurate temperature prediction, it is necessary to use a COF value that is close to the COF value which is present in the experiment.

The information presented in this current study helps to predict the temperature for a specific forming process for given process conditions. Using this information, the effect of temperature upon lubricant performance in stamping can be better understood so that for a given application, lubricants may be selected, based on quantitative information. Furthermore, prediction of interface temperatures will also lead to understanding and possible prediction of tool wear in stamping.

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