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Temperature conditions during ‘cold’ sheet metal stamping

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Abstract

This paper investigates the friction and deformation-induced heating that occurs during the stamping of high strength sheet steels, under room temperature conditions. A thermo-mechanical finite element model of a typical plane strain stamping process was developed to understand the temperature conditions experienced within the die and blank material; and this was validated against experimental measurements. A high level of correlation was achieved between the finite element model and experimental data for a range of operating conditions and parameters. The model showed that the heat generated during realistic production conditions can result in high temperatures of up to 108°C and 181°C in the blank and die materials, respectively, for what was traditionally expected to be 'cold' forming conditions. It was identified that frictional heating was primarily responsible for the peak temperatures at the die surface, whilst the peak blank temperatures were caused by a combination of frictional and deformation induced heating. The results provide new insights into the local conditions within the blank and die, and are of direct relevance to sheet formability and tool wear performance during industrial stamping processes.

Keywords: Advanced high strength steels; Metal forming; Temperature; Thermo-mechanical finite element model; Tool wear
1. Introduction

The increased use of advanced high strength steels (AHSS) in the automotive industry has resulted in an increase in formability and wear issues during stamping production. To successfully stamp AHSS, experience from the stamping press shop shows that press speeds and production rates often need to be reduced to minimize work-piece splitting and/or tool wear problems. This indicates that friction and deformation-induced heating are of significance to the stamping of higher strength sheet steels, for what is expected to be ‘cold’ forming conditions.

The phenomena of deformation-induced heating and frictional heating are well known and have been discussed in the literature for many years. For example, the early work by Farren and Taylor (1925) showed that approximately 90% of the work done is converted to heat during the rapid plastic deformation of several metals. Archard (1959) described the theoretical maximum flash temperatures that occur at the surfaces of rubbing materials, where nearly all the energy dissipated by friction appears as heat. The effect of this deformation-induced and frictional heating on the lubrication and wear performance for sheet metal ironing processes has been studied recently, with temperatures in the order of 100°C observed near the tool surface for the ironing of stainless steel sheet (Nielsen et al., 2011). However, the analysis of friction and deformation-induced heating during room temperature sheet metal stamping has received little attention in the literature. Due to the increased work and contact pressures required to form the higher strength sheet materials (Pereira et al., 2008), significant temperatures can be generated at the blank and tool surfaces during stamping processes.

Recently, there have been a few studies that have used finite element analysis (FEA) to examine the temperatures generated in the blank and/or die during continuous bending-under-tension-type processes. Groche et al. (2008) predicted that small temperature rises (less than 20°C) can occur at the die radius region during the strip drawing of aluminum at 100 mm/s. For a draw-bending process, Kim et al. (2011) predicted that temperatures of up to 100°C can occur in dual-phase (DP) steel blank material during industrial-type deformation rates (approximately 50 mm/s). Groche et al. (2008) showed that the peak temperature regions corresponded to regions of galling on the tool surface, while Kim et al. (2011) concluded that the deformation heating has a significant influence on the failure behavior of the sheet material.
The effects of friction and deformation-induced heating during discontinuous stamping-type processes have received less attention in the literature. Considering an axisymmetric cup forming process, Kim et al. (2009) used finite element modeling to predict that a dual phase steel (DP590) blank and D2 tool steel die could reach maximum temperatures of 86°C and 46°C, respectively. Pereira et al. (2010a) predicted that temperatures of over 100°C can occur at the die radius when stamping AHSS sheet grades (DP590 and DP780) using D2 steel tools. Interestingly, the results by Pereira et al. (2010a) showed that the peak temperature rise would occur at the beginning of the die radius, with the largest temperature rise occurring at the die (not blank) surface. The results presented by Kim et al. (2009) showed the opposite behavior – i.e. the maximum temperature on the die was predicted to occur towards the end of the radius, while the maximum temperature rise on the blank was more than double that on the die. It is evident that further work is required to understand the temperature behavior in both the sheet and die material during sheet metal stamping. This is particularly important when considering the high temperatures predicted to occur when forming high strength steels and the high process speeds used in many automotive stamping press lines.

The studies discussed in the preceding paragraphs do not provide quantitative comparison of the finite element model temperature predictions to experimental temperature measurements. Therefore, there is also a need to provide experimental validation for the temperatures predicted, to provide confidence in the numerical models.

This study examines the friction and deformation-induced heating of high strength sheet steels during sheet metal stamping. A novel semi-industrial stamping test facility was instrumented to provide temperature measurements at the die radius region, both at the die-to-blank interface and below the die surface. A thermo-mechanical finite element model of the semi-industrial channel forming process was developed. The model demonstrates good agreement with experimental measurements of punch force, blank and die surface temperature and die bulk temperature during a low speed stamping operation for two blank material grades. The developed finite element model was then applied to replicate the true ram speed during production-type operating conditions – i.e. when the rate of the mechanical press is 32 strokes per minute. Consequently, the results provide new insights into the temperatures that occur within the die and blank material during industrial cold sheet metal stamping conditions. Finally, the model was utilized to highlight some of the factors that strongly influence the temperature rise in the blank and die during sheet metal stamping.
2. Experimental setup

2.1. Process, geometry and operating conditions

Fig. 1a shows the left side of the tooling of the semi-industrial stamping test, which forms the basis of this study. A single-action mechanical press was used to stamp the channel-shaped components, with the geometric and process parameters (detailed in Table 1) closely representing that of a typical automotive structural member. This section provides aspect of the experimental set-up relevant to this study. A full description of the experimental set-up is available in Pereira et al. (2013).

![Fig. 1: (a) Schematic of the tooling setup for the sheet metal stamping process. (b and c) Schematic of thermocouple placement, showing section view of die corner inserts (not to scale).](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average blank holder force</td>
<td>27.2</td>
<td>kN</td>
</tr>
<tr>
<td>Average ejector pin force</td>
<td>1</td>
<td>kN</td>
</tr>
<tr>
<td>Blank length, l</td>
<td>150</td>
<td>mm</td>
</tr>
<tr>
<td>Blank width</td>
<td>26</td>
<td>mm</td>
</tr>
<tr>
<td>Blank thickness, t</td>
<td>1.8, 2.0</td>
<td>mm</td>
</tr>
<tr>
<td>Die corner radius, rd</td>
<td>5</td>
<td>mm</td>
</tr>
<tr>
<td>Draw depth</td>
<td>40</td>
<td>mm</td>
</tr>
<tr>
<td>Press stroke length</td>
<td>203</td>
<td>mm</td>
</tr>
<tr>
<td>Punch corner radius, rp</td>
<td>5</td>
<td>mm</td>
</tr>
<tr>
<td>Press rate</td>
<td>1, 32</td>
<td>min⁻¹</td>
</tr>
<tr>
<td>Punch width, a</td>
<td>30</td>
<td>mm</td>
</tr>
<tr>
<td>Punch-to-die gap, g</td>
<td>2.35</td>
<td>mm</td>
</tr>
</tbody>
</table>

The tooling setup permitted control of the blank holder force, via gas springs. The magnitude of the blank holder force was chosen to be sufficient to maintain closure of the blank holder
during the forming stroke, as determined from finite element model calculations. The punch force was recorded during the stroke using a piezoelectric load cell that was located below the punch. For all stamping tests, the blank material was lubricated with a thin film of anti-corrosive oil, as delivered from the steel mill.

The mechanical press operated continuously at 32 strokes per minute. At this press rate, the punch speed is approximately 300 mm/s at the beginning of the forming operation and reduces to 0 mm/s at the end of the 40 mm forming stroke (see Fig. 2a), as governed by the geometry and kinematics of the press and tooling system and the press crankshaft rotational speed. The mechanical press could also operate at a much slower speed of approximately 1 stroke per minute (normally used for process setup, etc.). This press rate resulted in a punch speed of approximately 8 mm/s and 0 mm/s at the beginning and end of the sheet metal forming operation, respectively (see Fig. 2b). For convenience, the two press operation modes will be subsequently denoted as ‘high speed’ and ‘low speed’. As shown in Fig. 2, the duration of the forming stroke is approximately 0.25 and 8.9 seconds for the high and low speed modes, respectively.

![Fig. 2: Punch speed and displacement during the forming stroke for the (a) high speed and (b) low speed stamping test settings.](image)

2.2. Temperature measurements

A J-type thermocouple, with an exposed junction and 0.2 mm diameter wire, was used to measure temperature during the stamping operation at the two locations shown in Fig. 1b and 1c. In both cases, a 1 mm diameter hole was drilled from the rear of the die insert to allow
placement of the thermocouple, ensuring that the temperature measurement was close to the middle of the blank-die contact region, where the approximately plane strain conditions exist. For the case shown in Fig. 1c, the thermocouple was located 2.2 mm below the tool surface, at the angular position of $\theta=40^\circ$ along the die radius, thus providing bulk temperature measurements close to the die radius surface. For the case shown in Fig. 1b, the thermocouple was positioned so that it protruded slightly from the die, at the location of $\theta=8^\circ$ on the die surface. The compliance provided by the length of the thermocouple wire along the drilled hole ensured that the presence of the thermocouple did not alter the contact between the blank and die, but still ensured firm contact with the blank material as it moved over the die radius during the stamping process. Therefore, the ‘interface’ temperature at the blank and die surfaces was measured, because the thermocouple contacted both the blank and die surfaces during the stamping operation.

The thermocouple response time is in the order of tens of milliseconds, but the temperature could only be recorded at a maximum sampling rate of 1 Hz. Therefore, the temperature measurements were performed during the low speed press mode, to allow the measurement of the temperature response during the 8.9 second forming stroke. The temperature response of the system during the low speed forming mode was examined in detail in order to establish the likelihood of obtaining accurate temperature measurements for the given instrumentation setup. For example, the finite element model showed that, at the point where the maximum temperature rise occurs, the blank speed is less than 5 mm/s and that the blank surface temperature varies by less than 1°C at a distance of 1 mm either side of the measurement location. As such, it is believed that the combination of the rapid thermocouple response time, small size of the thermocouple, relatively slow movement of the blank and relatively low temperature gradient in the die and blank materials, ensured that accurate temperature measurements could be obtained during the low speed operating conditions. However, using this experimental setup, it is not possible to obtain accurate temperature measurements during the high speed test conditions.

### 2.3. Materials

Two blank materials were examined in the experimental study – a 2.0 mm thick dual phase grade steel (DP780) and a 1.8 mm thick high strength low alloy grade steel (HSLA400). Two other material grades – DP590 and HSLA300 – were also examined in the numerical study. Table 2 shows the mechanical properties of the four blank material grades examined, as determined from quasi-static ambient temperature tensile tests. The tensile tests were
conducted in accordance with Australian Standard AS 1391-1991, at room temperature, in the
direction of forming (transverse to the sheet rolling direction), using a screw-driven test
frame, with crosshead speed of 0.083 mm/s and 25 mm nominal gauge length for the tensile
specimens.

Table 2: Mechanical properties of blank materials examined in this study.

<table>
<thead>
<tr>
<th></th>
<th>HSLA300</th>
<th>HSLA400</th>
<th>DP590</th>
<th>DP780</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength [MPa]</td>
<td>321</td>
<td>447</td>
<td>400</td>
<td>587</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
<td>485</td>
<td>525</td>
<td>659</td>
<td>884</td>
</tr>
<tr>
<td>Uniform elongation [%]</td>
<td>19.2</td>
<td>16.8</td>
<td>16.2</td>
<td>8.3</td>
</tr>
</tbody>
</table>

3. Numerical setup

The channel forming process was analyzed using an implicit finite element code,
Abaqus/Standard v6.10-1 (Dassault Systèmes Simulia Corp., 2010). A non-linear, transient,
thermal-stress analysis was conducted. The problem was simplified to a one-half symmetric,
two-dimensional, plane strain problem. The finite element mesh and numerical parameters
relating to the non-linear stress solution were based on the previous finite element models of
the channel forming process developed by Pereira et al. (2008 and 2010a), and therefore will
not be repeated here.

The important parameters relating to the thermal-stress solution are summarized in Table 3.
The values of these parameters were carefully chosen to ensure all values were reasonable and
were within the range of values specified in relevant numerical studies presented in the
literature (Gåård et al., 2010; Kim et al., 2011; Pei et al., 2003). The parameters relevant to
the blank material and tools (die, holder, punch) are based on the properties of low carbon
steel and tool steel, respectively. Additionally, the plastic flow curves for the blank materials
were entered based on tabulated tensile test data for the four grades detailed in Section 2.3.
The inelastic heat fraction, $\eta_I$, and friction energy heat dissipation fraction, $\eta_F$, relate to the
amount of work from plastic deformation and friction that is converted into heat. The friction
heat factor, $\xi$, of 0.5 indicates that the frictional heat generated at the blank-tool interface
during sliding contact is distributed evenly into the two surfaces. The contact thermal
conductance represents the heat transfer coefficient between the tools and blank – i.e. the
metal-to-metal contact. It is known that this parameter is pressure dependent; however, for
simplicity, it was set as a constant value.
Given the time scale of the forming operation and relatively low temperatures involved in the stamping process, the effects of convection and radiation were assumed to be negligible, and were not modeled. Furthermore, the strain rate and temperature dependence of all material parameters were ignored for this analysis. This simplification is reasonable, considering that the die is modeled as a linear elastic solid and that the maximum temperature experienced in the elastic-plastic blank is generally less than 100°C, apart from a few localized regions.

Table 3: Important parameters relating to the thermal calculations for the thermo-mechanical finite element model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tools</th>
<th>Blank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg.mm^{-3}]</td>
<td>$7.7 \times 10^{-6}$</td>
<td>$7.9 \times 10^{-6}$</td>
</tr>
<tr>
<td>Expansion coefficient [°C^{-1}]</td>
<td>$12 \times 10^{-6}$</td>
<td>$12 \times 10^{-6}$</td>
</tr>
<tr>
<td>Specific heat capacity [J.kg^{-1}.°C^{-1}]</td>
<td>460</td>
<td>480</td>
</tr>
<tr>
<td>Thermal conductivity [J.s^{-1}.m^{-1}.°C^{-1}]</td>
<td>22</td>
<td>52</td>
</tr>
<tr>
<td>Contact thermal conductance [J.s^{-1}.m^{-2}.°C^{-1}]</td>
<td>$20 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Ambient temperature [°C]</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Friction energy heat dissipation fraction, $\eta_F$</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Friction heat distribution factor, $\xi$</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Inelastic heat fraction, $\eta_I$</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Friction coefficient, $\mu$</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

The punch movement was specified via a displacement boundary condition using tabulated amplitude data to accurately represent the experimental scenario (see Fig. 2). Due to the gas springs used for the blank holder and ejector pins, the magnitude of the blank holder force and ejector pin force increases approximately linearly from the beginning of the forming stroke to the end of the forming stroke by approximately 20%. This effect was included in the model in the loading conditions, and is observed by the increasing punch force curves during the forming stroke in both the experimental and numerical cases (see Fig. 3).

4. Results and discussion

To develop and validate the thermo-mechanical finite element solution, the low speed forming conditions were first replicated for both stamping conditions and blank materials and validated against the experimental measurements. Subsequent models, representing the high punch speed test condition and different material and process parameters, were based on the initial developed model. All experimental and numerical temperature results are based on a single stamping operation, beginning from ambient operating conditions.
4.1. Low speed stamping conditions and model validation

The punch force curves predicted using the developed finite element models are compared to the measured punch force curves in Fig. 3, for the DP780 and HSLA400 blank material grades during the low punch speed operational mode. Note that the corresponding values of time at 10, 20, 30 and 40 mm of punch travel are shown on the secondary horizontal axes labels in Fig. 3 for reference. For each material grade, five experimental curves are shown, highlighting the consistency of the experimental data. It is evident that the numerically predicted punch force is in very good agreement with the experimental measurements for both forming conditions.

![Fig. 3: Experimentally measured and numerically predicted punch force during the low speed stamping operation for (a) DP780 and (b) HSLA400 blank material.](image)

The experimental punch force curves show a small increase in magnitude near the end of the stroke (at approximately the last 3 mm of punch travel). Due the varying speed of the punch during the stroke, the punch speed is less than 2.5 mm/s at this stage. This behavior is not evident during the high speed stamping mode and is therefore likely to be due to the increased friction between the blank and tools (and possibly stick-slip behavior) as a result of the low sliding speeds between the blank and tools at the end of the forming stroke. The finite element models do not capture this behavior due to the constant coefficient of friction used.

The measured and predicted temperature rise at the blank-die interface at $\theta=8^\circ$ on the die surface (see Fig. 1b) throughout the duration of the forming stroke is shown in Fig. 4. Similarly, the measured and predicted temperature rise at the location $\theta=40^\circ$ at 2.2 mm below the die surface (see Fig. 1c) is shown in Fig. 5. For each condition, the temperature was continually recorded, showing the decay in temperature after the end of the forming stroke.
However, the finite element model predictions consider the forming stage only – i.e. from 0 to 40 mm of punch travel, corresponding to the time period of 0 to 8.9 seconds. For this reason, the secondary horizontal axes labels in Fig. 4 show the corresponding values of punch travel at the process time of 0, 2, 4, 6 and 8 seconds for reference. The temperature rise above ambient temperature is shown to permit easy comparison and thus allow the small differences in the ambient temperature between the experimental measurements to be excluded.

![Fig. 4: Measured and predicted temperature rise during low speed stamping operation at the die-blank interface (at location $\theta=8^\circ$) for (a) DP780 and (b) HSLA400 blank material.](image)

The experimental results in Figs. 4a and 4b show qualitatively similar behavior, with the temperature rising rapidly and the peak temperature occurring at approximately 4 seconds. In Figs. 5a and 5b the rates of temperature rise and peak temperatures are lower, due to the time and dissipation associated with the heat conduction from where it is generated at the die

![Fig. 5: Measured and predicted temperature rise during low speed stamping operation at 2.2mm below the die surface (at location $\theta=40^\circ$) for (a) DP780 and (b) HSLA400 blank material.](image)
surface to the position of the thermocouple below the die surface (see Fig. 1c). However, Figs. 4 and 5 show that the temperature rise at the interface for the DP780 material case is consistently higher than that for the HSLA400 material. This is due to the increased friction and deformation-induced heating caused by the higher strength and larger thickness of the DP780 sheet material.

The finite element model predictions of temperature rise at the two locations shown in Figs. 4 and 5, show good agreement with the temperature measurements for both blank material conditions, with both the magnitude and the trend of the results correlating well. This high level of correlation between the FEA results and the experimental forming data, for the range of operating conditions, materials and parameters examined, provides a strong level of confidence in the model predictions. Furthermore, the correlation to the experimental data for the two blank material conditions simulated was achieved with sensible/realistic thermal and frictional FEA parameters shown in Table 3. This indicates that the developed model can accurately simulate the mechanical response and the friction and deformation-induced heating behavior during the typical sheet metal stamping process examined and therefore can be applied to other operating conditions.

4.2. High speed stamping conditions

The finite element model developed in the previous section was applied to analyze the friction and deformation-induced heat generation in the blank for the high speed stamping conditions (i.e. replicating the true ram speed of the semi-industrial stamping operation running at 32 strokes per minute – see Fig. 2a). This section discusses the results for the DP780 blank material and operating conditions only, as the forming of AHSS is of primary interest.

4.2.1. Maximum temperature

From a tool wear and sheet formability perspective, the maximum temperature experienced by the die and blank is of primary concern. Fig. 6a shows the predicted maximum temperature for the blank and die at any given instant during the stamping process, for both the low and high speed forming conditions using the DP780 material. Fig. 6b shows the maximum temperature that occurs over the die radius region for the die and blank materials. In this figure, the maximum temperature on the blank surface is shown with respect to the position of the blank when this maximum temperature occurred (relative to the die radius). Conversely, Fig. 6c shows the maximum temperature distribution over the blank surface with respect to the final location on the formed blank surface. Consideration of the three graphs in
Fig. 6 together allows the reader to determine the magnitude, time and location at which the maximum temperature occurs during the stamping process on the die and blank (as indicated by the circle and square markers, respectively). Therefore, Fig. 6 shows that the predicted maximum temperature on the die during the high speed stamping is 181°C, occurring when the punch has travelled 23 mm and at a location of $\theta=6^\circ$ on the die radius (0.5 mm from the beginning of the die radius). Similarly, the maximum temperature on the blank is predicted to be 108°C, occurring at 9.8 mm punch travel at a location of $\theta=62^\circ$ (which corresponds to the final location on the sidewall of the formed part of 32 mm from the bottom of the channel, as shown).

Fig. 6: Predicted maximum temperature on the blank and die surfaces for DP780 material grade during high and low speed stamping conditions.
The maximum temperature distribution during the low speed stamping condition is shown in Fig. 6 for reference, highlighting the strong influence of process speed on the temperatures generated. The peak temperature rise in the die and blank during the low speed stamping operation is 85% and 64% lower, respectively, compared to the high speed stamping operation. Interestingly, during the low speed stamping operation, the blank temperatures are higher than the die temperatures and the maximum temperature in the blank occurs towards the end of the die radius region (see Figs. 6a and 6b).

4.2.2. Contribution of friction and deformation-induced heating

To determine the individual contribution of the frictional heat generation and deformation-induced heating to the maximum temperature on the blank, two separate finite element models were run with the inelastic heat fraction, \( \eta_I \), and friction energy heat dissipation fraction, \( \eta_F \), individually set to zero. Figs. 7a and 7b show that the frictional heating contributes mostly to the temperature rise experienced at the die surface, with the maximum temperature reduced by only 5.2% when \( \eta_I \) is set to zero. Conversely, Figs. 7c and 7d show that the friction and deformational-induced heating both contribute strongly to the overall temperature rise in the blank material. It is evident that when the influence of frictional heating is ignored, the peak temperature at the blank during the initial stage of the process is not captured.
Fig. 7: The effect of friction and deformation-induced heating on the maximum temperature experienced at the die and blank surfaces during high speed forming conditions.

It is worth noting that contributions of frictional and deformation-induced heating to the maximum temperature is not a linear effect and therefore cannot simply be added to produce the final maximum temperatures shown in Fig. 7. The interactions are complex and the direction of heat transfer can change, depending on the scenario and location. Additionally, Fig. 7 shows the maximum temperature, but the location at which this occurs (not shown) varies for each scenario and throughout the process.

4.2.3. Evolution and distribution of temperature
To obtain a better understanding of the peak temperature response over the die and blank surfaces, contour plots of the predicted temperature are shown in Figs. 8 and 9. Using the method described previously for contact pressure (Pereira et al., 2008), the distribution of temperature over the die radius and its evolution throughout the stamping process was
determined and is shown in Fig. 8a. Similarly, the temperature evolution and distribution over the blank surface, with respect to its relative position on the die radius throughout the forming process, is shown in Fig. 9a.

Fig. 8 shows that the temperatures generated at the die radius surface are complex and time-dependent. However, it is evident that the temperature response shows qualitative similarities to the contact pressure behavior presented previously for a similar stamping process (Pereira et al., 2008), with strong evidence of the distinct transient and steady contact phases (Pereira et al., 2009). This result is expected, considering that the rise in surface temperature is a consequence of the contact conditions experienced. In particular, the amount of frictional heat generated is closely related to the magnitude of the contact pressure, while the heat generated by plastic deformation only occurs at the blank since the tools are assumed to be elastic. Furthermore, the deformational heat from the blank can only be transferred to the die surface when there is contact between the blank and die surfaces, and therefore does not have much effect on the die temperatures (as shown in Figs. 7a and 7b).

Despite these effects, there are some notable differences between the contact pressure and temperature behavior because large temperatures can effectively accumulate at regions that remain in frictional contact with the blank surface for longer periods of time. For example, although the transient stage results in the highest contact pressures at the die surface at approximately 9 mm of punch travel, the maximum temperature on the die does not occur at this region (see Fig. 8b). The high contact pressures, but small sliding distances, experienced by the die at the location near $\theta=55^\circ$ results in peak temperatures of up to 105°C. During the later stage of the process the peak contact pressures are reduced, but the sliding distance experienced by the die is much higher. This is evident at 23 mm of punch travel, where the temperature is approximately 181°C at the location near $\theta=6^\circ$, as shown in Fig. 8c.
Fig. 8: Temperature at die radius region for DP780 material grade. (a) Evolution and distribution of temperature at die surface during forming stroke. Contours of temperature at die radius region at (b) 9 mm and (c) 23 mm of punch travel. The images on the right show 2D contours extruded for visualization purposes to highlight temperatures at die surface.

Fig. 8 shows that the heat generated at the die surface is rapidly conducted away into the bulk die material. For example, at $\theta=56^\circ$ when the punch has travelled 9.3 mm, the predicted temperature is 105ºC. Soon after this instant, this region does not contact the blank for the remainder of the process – i.e. there is zero contact pressure at this point between approximately 10 and 40 mm of punch travel. With no further heat input at the die surface, the heat is quickly conducted away. At only 6 milliseconds after the severe contact / peak temperature event, when the punch travel is 10.9 mm, the temperature at the same location ($\theta=56^\circ$) has reduced to 50ºC (i.e. reduced by 55 ºC). This fast dissipation of heat is also
evident at the end of the stamping process (as shown in Figs. 6a and 8a), as the peak temperatures in the die reduces significantly near the end of the stamping process due to the slowing punch speed (see Fig. 2a).

The temperatures generated in the blank are also complex and time-dependent. The peak temperatures in the blank occur at the top (outer) surface which contacts the die. However, the blank peak temperatures are lower than those of the die because fresh blank material continually enters the contact zone. A single point on the blank does not experience more than approximately 5 mm of sliding contact with die radius (Pereira et al., 2010b) and, as a result, does not accumulate temperature in the same manner that occurs with the die.

Fig. 6a shows that the maximum temperature generated in the blank for most of the process is above 80°C; while Fig. 6c shows that a large proportion of the sidewall of the formed part...
experiences these high temperatures. Fig. 9 reveals that the higher temperatures in the blank are localized at three distinct locations with respect to the die radius region during the stamping process – i.e. at locations of approximately 1, 5 and 10 mm from the beginning of the die radius. Figs. 9b to 9d show the instances at which these high temperatures on the blank occur.

The first location, shown in Fig. 9b, corresponds to the region where the highest blank temperature during the stamping process is reached (108°C). As shown, the maximum temperature occurs over a very small region of the blank, near \( \theta = 60^\circ \) on the die radius, and over a short period of time as it experiences high contact pressure sliding contact with the die radius. This region of highest contact pressure and highest temperature on the blank corresponds to the die impact line region on the sidewall surface of the formed part, as identified by Pereira et al. (2010b). Analysis of the models discussed in Section 4.2.2 reveals that frictional heating is primarily responsible for the temperatures generated at this location.

The second location of high temperatures in the blank material occurs near \( \theta = 10^\circ \) on the die radius and occurs for a large proportion of the stamping process (from approximately 10 to 35 mm of punch travel), as shown in Figs. 9a to 9d. Analysis of the models discussed in Section 4.2.2 shows that frictional heating (due to the moderate contact pressures and sliding distances) is largely responsible for the peak temperature generated at this region. However, the deformation-induced heating (due to the bending of the blank material around the die radius) also influences the temperature at this region to a lesser extent.

The third high temperature region, shown in Fig. 9d is at 9.5 mm from the beginning of the die radius (i.e. in the sidewall region of the part, \( \theta > 90^\circ \)). This also occurs for a large proportion of the stamping process, from approximately 20 to 40 mm of punch travel (see Fig. 9a). The models discussed in Section 4.2.2 reveal that deformation-induced heating (due to the unbending of the blank material from the curved die radius region to straight sidewall), causes the majority of the temperature rise in this region. Although the blank does not contact the die radius in this region, friction-induced heating still partially contributes to the peak temperature because the material in this region previously experienced sliding contact with the die radius earlier in the stamping process and therefore experienced frictional heating.

It is evident that the regions on the blank where frictional heating is dominant, result in only localized heating at the blank surface (see Figs. 9b and 9c). Conversely, at the areas where
deformation-induced heating is dominant, the increased temperature is distributed further into
the blank material.

4.2.4. Effect of material strength on peak temperatures
To examine the effect of the blank material strength on the maximum temperatures that occur
in the die and part, the four blank material grades shown in Table 2 were simulated with a
sheet thickness of 2 mm. Fig. 10 shows the effect of the four material grades on the
maximum temperature in the blank and die. It is evident that the maximum temperature is
strongly influenced by the blank material strength, with the results showing an almost linear
relationship between tensile strength of the blank material and the peak die and blank
temperatures. The non-linear relationship between the predicted maximum temperature and
the yield strength is due to the different work hardening behavior in the steel grades
examined; with the HSLA400 material grade exhibiting a higher yield to tensile strength ratio
compared to the other grades examined. It can be concluded that the large temperature rise
observed is due to the increased contact stresses and increased plastic work associated with
 stamping the higher strength material grades. Therefore, it is conceivable that the trend
towards higher strength steels in the automotive industry may need to be offset by a reduction
in press speeds in order to reduce the likelihood of sheet formability and tool wear problems.

![Graph showing the effect of material strength on peak temperatures](image)

Fig. 10: Effect of blank material yield strength and tensile strength on the predicted maximum temperature on
the blank and die during the high punch speed operation.

4.3. Discussion
This study has shown that the predicted peak temperature at the die for the DP780 material
case is approximately 180°C. This temperature is above the temperatures reported by van der
Heide and Schipper (2003) for lubricant breakdown. Additionally, according to the Lim and
Ashby (1987) wear mechanism and temperature maps for un lubricated steel-on-steel sliding
contact, this predicted peak temperature is close to the temperatures at which the ‘cold’ mechanical wear mechanisms are no longer dominant. For the typical cold mechanical wear mechanisms, such as wave removal, micro-cutting and ploughing, the wear rate (per unit sliding distance) depends primarily on contact pressure. However, for the ‘hot’ wear mechanisms, thermal and chemical effects, including oxidation, are important and the wear rate becomes dependent on contact pressure and sliding velocity (Williams, 1999). This speed/temperature effect is anecdotally evident in the automotive sheet metal stamping industry, where it is generally thought that reducing the press speed when stamping AHSS can result in reduced tool wear (Sandberg et al., 2004). Furthermore, the peak die surface temperatures predicted in this study correspond to the temperature range where Okonkwo et al. (2012) have observed a transition in dominant wear mechanisms during steel on tool steel. The predicted peak temperatures in the blank material shown in this study (circa 100°C) are of similar magnitude to those predicted by Kim et al. (2011) for draw-bending of dual-phase steel sheet at industrial-type deformation rates. Furthermore, Kim et al. (2011) showed that these moderate temperatures (in the order of 75°C) can significantly affect the forming limits of the blank material. The results shown in this investigation show that the stamping of high strength steels can result in blank temperatures of this magnitude or greater, indicating that the corresponding effect on the forming limits may need to be considered.

Finally, it is worth noting that the temperature predictions reported in this investigation are based on a single industrial stamping operation, beginning from ambient operating conditions. Therefore, it is likely that continuous operation of the stamping process, forming numerous parts per minute, will result in further increases in the blank and die temperatures, as indicated by recent experimental measurements conducted by Hazra et al. (2011) for a stamping process in a production environment.

5. Conclusions

This paper used a combination of experimental and numerical methods to investigate friction and deformation-induced heating during the stamping of high strength and advanced high strength sheet steels. It was shown that stamping high strength steels at realistic production operating conditions can result in high temperatures in the blank and die, for what is traditionally expected to be ‘cold’ forming conditions. The results of this study provide new
insights into the conditions that occur within the blank and die and are of direct relevance to sheet formability and tool wear performance during industrial stamping processes.

For the DP780 case examined, it was found that:

- Frictional heating is primarily responsible for the peak temperatures at the die surface, with the maximum temperature on the die was predicted to be 181°F near the beginning of the die radius.

- The predicted peak temperature on the blank was 108°F with frictional heating also the primary cause for the temperature rise. The peak temperature occurred as the blank interacts with the die during the initial transient stage of the process at a location on the blank corresponding to the die impact line region of the sidewall of the final part.

- High temperatures (>80°C) generated over a large regions of the blank are strongly influenced by the plastic deformation-induced heating, as a result of the bending and unbending of the blank material.

This study also showed that the maximum temperature in the die and blank is strongly influenced by the blank material strength and process speed. For the range of material grades examined, an almost linear relationship between tensile strength of the blank material and the peak die and blank temperatures was predicted.

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References


Figure captions

Fig. 1: (a) Schematic of the tooling setup for the sheet metal stamping process. (b and c) Schematic of thermocouple placement, showing section view of die corner inserts (not to scale).

Fig. 2: Punch speed and displacement during the forming stroke for the (a) high speed and (b) low speed stamping test settings.

Fig. 3: Experimentally measured and numerically predicted punch force during the low speed stamping operation for (a) DP780 and (b) HSLA400 blank material.

Fig. 4: Measured and predicted temperature rise during low speed stamping operation at the die-blank interface (at location $\theta=8^\circ$) for (a) DP780 and (b) HSLA400 blank material.

Fig. 5: Measured and predicted temperature rise during low speed stamping operation at 2.2mm below the die surface (at location $\theta=40^\circ$) for (a) DP780 and (b) HSLA400 blank material.

Fig. 6: Predicted maximum temperature on the blank and die surfaces for DP780 material grade during high and low speed stamping conditions.

Fig. 7: The effect of friction and deformation-induced heating on the maximum temperature experienced at the die and blank surfaces during high speed forming conditions.

Fig. 8: Temperature at die radius region for DP780 material grade. (a) Evolution and distribution of temperature at die surface during forming stroke. Contours of temperature at die radius region at (b) 9 mm and (c) 23 mm of punch travel. The images on the right show 2D contours extruded for visualization purposes to highlight temperatures at die surface.

Fig. 9: Blank temperature for DP780 material grade. (a) Evolution and distribution of temperature at blank surface during forming stroke. Contours of temperature at (b) 10mm, (c) 16mm and (d) 25mm of punch travel. 2D contours extruded for visualization purposes to highlight temperatures at blank surface.

Fig. 10: Effect of blank material yield strength and tensile strength on the predicted maximum temperature on the blank and die during the high punch speed operation.

Table captions

Table 1: Summary of the main geometric and process parameters used in the stamping tests.

Table 2: Mechanical properties of blank materials examined in this study.

Table 3: Important parameters relating to the thermal calculations for the thermo-mechanical finite element model.