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Investigations on contact pressure in sheet metal forming of advanced high-strength steels

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Abstract

Increased demands for safety and environment concerns have led to a greater use of advanced high strength in the automobile industry. The consequent challenges to sheet metal forming processes include higher contact pressures between dies and blanks with resulting consequences in increased wear and failures. In this article a numerical model is applied to analyze contact pressure along the tool die radius, where wear is particularly severe. Several sheet metal materials are numerically investigated, in order to quantify the pressure distribution along the radii which in turn has important effects on tool wear. The results show that different materials, its strength and behavior affect not only the contact pressure, but also the contact distribution at different zones of analysis.

1. Introduction

Recent challenges in the automotive industry concerning the importance of energy efficiency and carbon neutrality have resulted in the increased use of high-strength-lightweight alloys such as aluminum, magnesium, and advanced strength steels (AHSS). Specifically, AHSS present higher strength levels and better hardening characteristics than conventional mild steels, making it ideal for applications where low weight and improved passenger safety are required (Matlock et al. 2012). However, the higher material strength and surface hardness contributes to higher contact pressures between the tooling and the work piece resulting in increased tool wear which can lead to insufficient product quality, interrupted production, and unexpected cost increases. Therefore, it is crucial to understand and predict the contact pressure and the influence of various material parameters on the magnitude of tool wear in order to help the forming industries to decrease costs, maintenance time or tooling failures (Cora and Koç 2009). In deep-drawing forming processes, the adhesive wear is caused by the localized bonding between contacting surfaces, which lead to transfer or loss of material from both surfaces. The adhesive wear volume (V) can be given by Equation (1) as a function of the material wear coefficient (k), the normal load (L), the sliding distance (s), and the hardness (H) of surface that is being damaged (Archard 1953).

$$\mathrm{V} = \frac{kLs}{H} \tag{1}$$

To apply Equation (1) in the finite element analysis, an integral form of the equation is required (Wang and Masood 2011). Therefore, the wear work, W (surface energy or work per unit area), after a total time, T, is expressed as: Equation (2)

$$\frac{\mathrm{V}}{kA} = \int_0^T \frac{L}{A}\, v_t dt \Leftrightarrow \mathrm{W} = \int_0^T p_t\, v_t dt \tag{2}$$

where p_t is the normal contact pressure, v_t is the sliding velocity at the time t and A represent the contact area. Consequently, to evaluate the wear and predict the tool life it is essential to determine the contact pressure, in particular its maximum values at the sliding interface (Pereira, Yan, and Rolfe 2008). Normally, the most severe tribological wear occurs in the die radius which usually presents a 90° circular section (Pereira, Yan, and Rolfe 2010).

In this paper it is presented a numerical investigation on the behavior of different materials having different strengths, from mild steel to advanced high strength steels, in order to understand the results for contact pressure distribution along die radius and the corresponding wear response on tooling during sheet metal forming.

2. Materials and Methods

The sheet metal materials selected for this study include a mild steel, DC04, a dual phase steel, DP600, a high strength low alloy steel, HSLA420, and a martensitic steel, 1200M. Table 1 describes the main properties of the selected sheet metal materials.

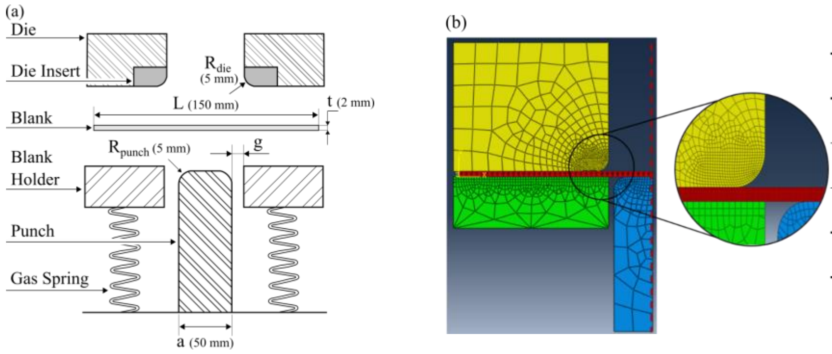
Table 1: Mechanical properties of sheet metal materials (SSAB 2017)

	Material	Young's modulus E [GPa]	Poisson's ratio ν	Specific mass ρ [kg/m^3]	Yield strength Re [MPa]	Ultimate Strength Rm [MPa]	Elongation [%]
Sheet material	DC04	210	0.3	7800	210	336	38
	DP600				443	640	17
	HSLA420				417	475	28
	1200M				1114	1309	4

In order to study the contact pressures and consequently the wear distribution, the selected forming process corresponds to a semi-industrial U-shaped tool, which replicates a typical sheet metal stamping die in the automotive industry.

The developed numerical models are based on Abaqus FEA code (Abaqus 2019). Additional work was performed in the development of scripts both in Python and Matlab to post-process results and create corresponding graphs.

This study will allow to reproduce the wear conditions for different materials and relate it with the variables of interest, e.g. the contact pressure (CPRESS) between die and blank. Figure 1(a) shows the tool layout to obtain the U-shaped component.



Tool	Number of elements
Punch	131 elements
Die	653 elements
Die Holder	333 elements
Total	1117 elements

Figure 1: Schematic representation of (a) tool geometry of the U-shaped geometry and (b) finite element mesh adopted in the numerical simulation (adapted from Pereira et al. (2013))

Regarding the numerical modelling, only half of the experimental setup was considered, due to symmetry conditions. The tool and sheet material are discretized using 4-node deformable solid elements (CPE4R from the Abaqus™ program library). The sheet material behavior is considered as elasto-plastic, while the tools present a pure elastic behavior. Figure 1(b) illustrates the finite element discretization of tools and blank.

The boundary conditions consider a punch displacement of 50 mm and the interaction between sheet metal and tool surfaces are defined by a tangential friction, with a Coulomb coefficient of 0.15 (Wang and Masood 2011).

The contact pressure will be studied along the die radius [0-90°] (see Figure 2(h)). The different simulation steps used for output of results correspond to different punch displacements between 0 and 50 mm, as shown in Figure 2(a-g).

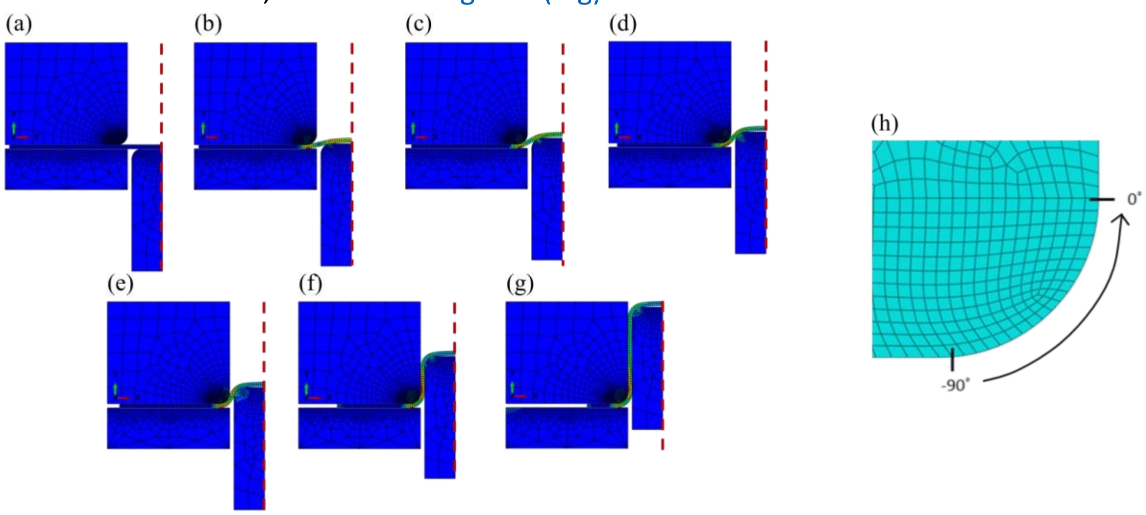


Figure 2: Stages of plastic forming of the U-shaped component for different punch displacements: (a) 0 mm; (b) 2.5 mm; (c) 5 mm; (d) 7.5 mm; (e) 10 mm; (f) 25 mm; (g) 50 mm; (h) selected die radius angles

3. Results and Discussion

The evolution of the contact pressure (CPRESS) for the selected materials as a function of the die angle is represented in Figure 3, considering the defined punch displacements for output of results, as shown in Figure 2.

As seen in Figure 3 the evolution of the contact pressure, globally, is similar for every material, although with distinct values: for a given punch displacement the 1200M material presents the highest contact pressure and DC04 the lowest, which follows their corresponding strength.

Looking in more detail for every output step of results there are some differences in material behavior. For a displacement of 2.5 mm (Figure 3(a)), all materials show a single pressure peak. In case of 5 mm punch displacement (Figure 3(b)), two pressure peaks are present, but 1200M steel behaves differently, not showing a 'zero contact' pressure between the two peaks. For a 7.5 mm (Figure 3(c)) and 10 mm (Figure 3(d)), every material presents two peaks of contact pressure, all of them with very similar behavior, being the second peak higher than the first and a resulting contact pressure being the highest from all punch displacements. For a punch displacement of 25 mm (Figure 3(e)), it is observed that all materials show two contact pressure peaks except the DC04 material which presents three distinct peaks. Regarding the zero-pressure zone, it can be observed that, for this displacement, the DP600 is the only material that does not present out of contact. Finally, for a punch displacement of 50 mm (Figure 3(f)) it can be seen that the 1200M and DP600 materials show two peaks of contact pressure, while the HSLA420 and DC04 materials present three peaks. The location of the first pressure peak and the zero-contact pressure zone is well defined. However, the second peak shows distinct locations for the different materials, with the DP600 material being the one with higher distance for contact.

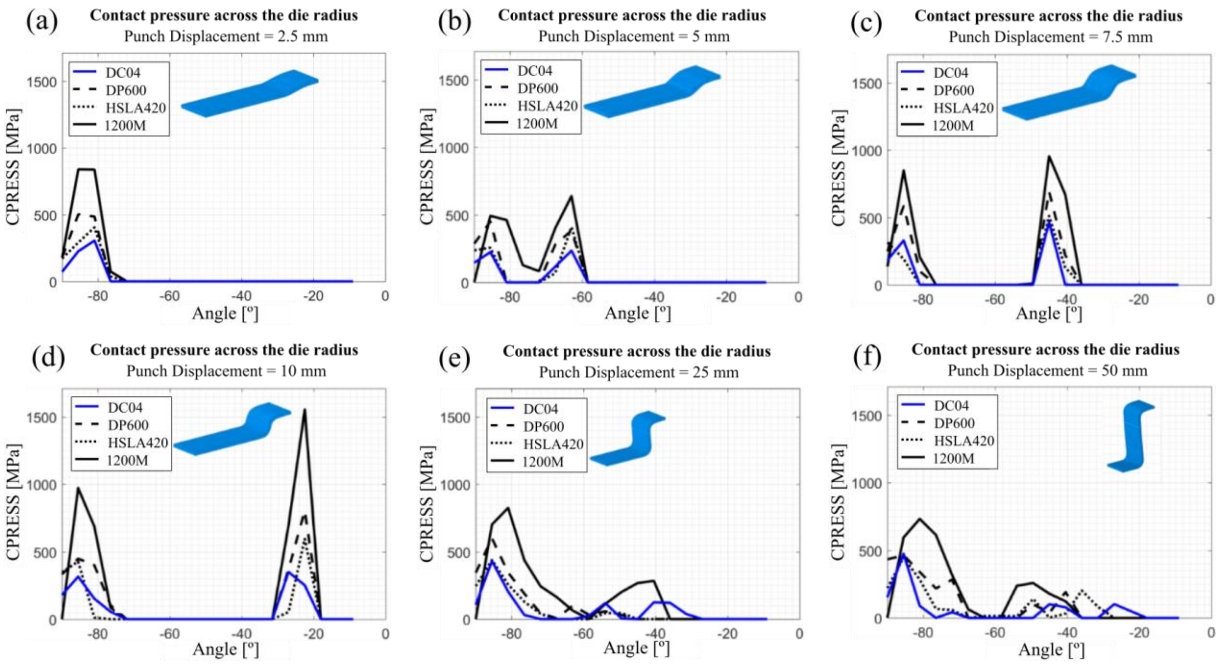


Figure 3: Evolution of the contact pressure along the die radius for different punch displacements: (a) 2.5 mm; (b) 5 mm; (c) 7.5 mm; (d) 10 mm; (e) 25 mm; (f) 50 mm

As described in the literature (Pereira, Yan, and Rolfe 2008) the contact pressure response can be divided into two distinct phases, a transient and steady-state one. It is possible to distinguish these phases analyzing Figure 4, which shows the contact pressure over the die radius as a color contour plot, for every punch displacement. When seeing the contact pressure for punch displacement between 16 and 50 mm, this region exhibits a constant contact pressure, which corresponds to approximately two-thirds of the process. This corresponds to the steady-state phase, in which the sheet metal undergoes a significant deformation during the punch displacement.

In case of region for punch displacement between 0 and 16 mm, the magnitude, location and distribution of the contact pressure along the die radius considerably changes, which corresponds to the transient phase and it is characterized by severe contact conditions.

In addition to the different phases mentioned above, three distinct zones can be highlighted as reported by Wang and Masood (2011), which are related by different mechanisms. In Zone 1, located near the -90° area of die radius (Figure 2), the sheet metal is constrained by the blank holder pressure and it is restricted from sliding over the die radius. Zone 2 is represented by a straight line from the bottom left corner to the right corner in the contour plots. The slope of this line is similar for every material, since it is only related to the die radius (Wang and Masood 2011). The maximum contact pressure is located in this zone and it is caused by the relative tangential slip motion between the sheet metal and the die radius, resulting in high contact forces at the tangential point. Finally, the Zone 3 corresponds to the -70° to -20° die radius region, in which different materials show a different behavior for initial vs. final contact.

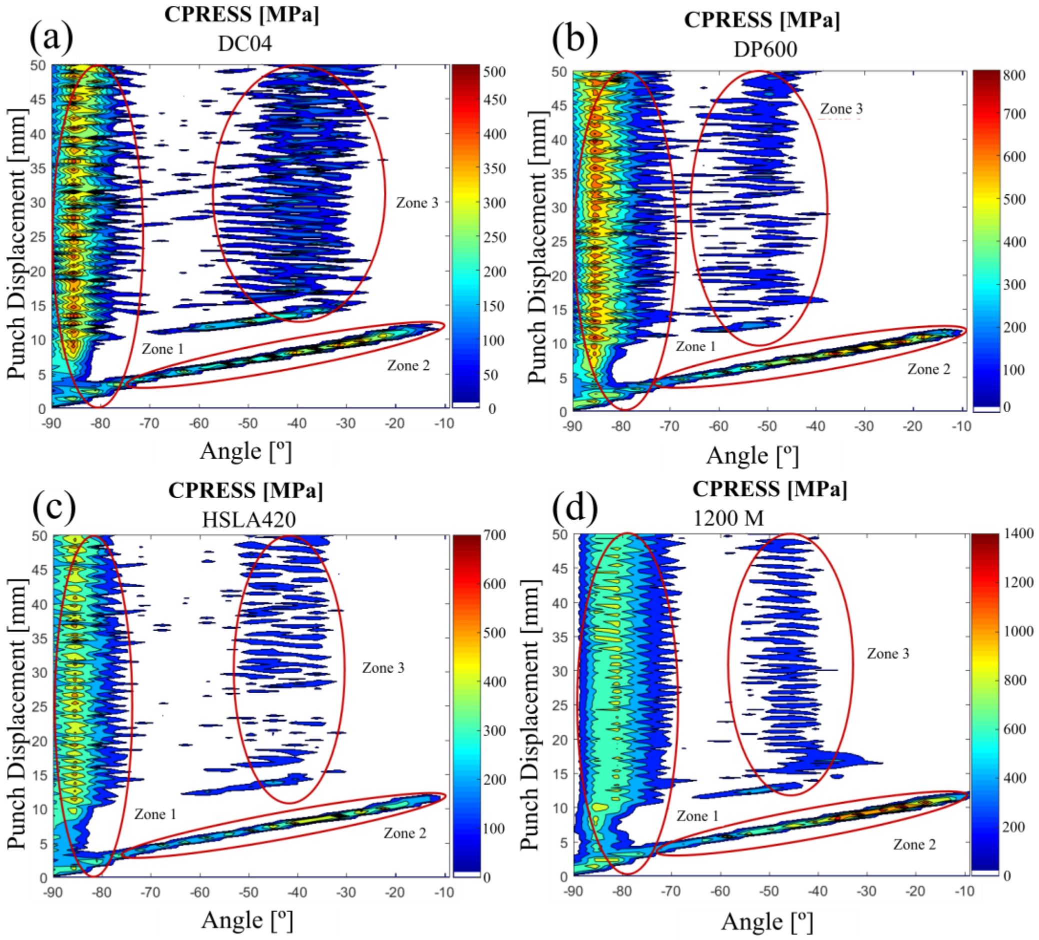


Figure 4: Evolution of the contact pressure (CPRESS) with punch displacement for (a) DC04, (b) DP600, (c) HSLA420, (d) 1200M materials along the die radius

4. Conclusions

In this work, a numerical investigation is presented using finite element analysis on the behavior of contact pressure and corresponding wear distribution for different materials in sheet metal stamping.

The developed numerical model is based on the plastic forming process of a semi-industrial component with U-shaped geometry, in order to test, characterize and quantify how different materials are related with contact pressure behavior. Selected materials in this study included a mild steel, DC04, a dual phase steel, DP600, a high strength low alloy steel, HSLA420, and a martensitic steel, 1200M.

The results show that different materials, with different strength, have their effect on the contact pressure. Contours showed that Zone 1 and Zone 2 are located in the same die position for every considered material, yet with distinct pressure magnitudes and a direct equivalence between strength of material and the corresponding result of contact pressure. On the other hand, Zone 3 has different behavior for different materials, both in position and size, and corresponds to a lower pressure region, being also a less critical zone. The results also suggest that contact pressure is mainly influenced by zones 1 and 2 and its minimization could be done by a change of die profiles from perfectly circular shape or also by increasing die radius, thus ensuring higher life of tooling, which will be a direction for further investigation.

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