Modeling of contact zones in air bending of sheet metals

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Abstract. Reducing unfavorable surface imprints, so-called “bending marks”, at the contact zones between the tools and the workpiece is a major objective in air bending of sheet metals. In this work basic numerical investigations of the contact zones were performed in order to study the mechanisms of bending mark formation. For that purpose a numerical model was created using the finite element software Abaqus. The two-dimensional model included the punch, the V-shaped die, the die insert and the steel sheet which has to be bent. All of these parts were treated as deformable. The elasto-plastic material properties required as input for the simulations were captured with uniaxial tensile tests. The influence of different insert materials on the plastic strain field inside the steel sheet was investigated. Air bending experiments were conducted for validating the results of the numerical simulations.

1. Introduction

Due to its high flexibility air bending has become an important sheet metal forming technology which is widely used in many branches of the production industry. In the classic three-point air bending process the metal sheet just contacts the radii of the V-shaped die and the tip of the punch, as shown in Figure 1 (a) and (b). In general, the process is easily adjustable and well controllable. However, as illustrated in Figure 1 (c) unfavorable linear surface imprints caused by the combination of high local pressure and relative motion usually occur at the contact zones between the tools and the metal sheet. Different measures, e.g. intense lubrication, soft or pivoting die inserts and protective bending films are applied for preventing the formation of these so-called “bending marks”.

Figure 1.
Air bending of 2 mm thick mild steel sheet using conventional tools (moving punch and fixed die): (a) initial punch position, (b) final punch position, (c) typical linear bending mark at the sheet surface.
Numerous analytical, numerical and experimental studies on three-point air bending of different sheet metals were conducted. These studies focused on process modeling [1]-[3], curvature prediction [4], springback prediction [5]-[11], or damage development and evolution [11]-[13]. However, to the authors’ knowledge no study has been investigating the mechanisms occurring at the contact zones between the tools and the sheet in detail. Therefore, the objective of the current work was to investigate the basic mechanisms causing the formation of bending marks by means of numerical simulations with particular focus on the analysis of stresses and strains occurring at the contact zones. The influence of different die inserts (steel insert vs. thermoplastic inserts) on the plastic deformation of the contact zone was evaluated for 90°-V-bending of mild steel sheets. The results of the simulations were experimentally validated. It should be noted that investigating the aforementioned phenomena, e.g. springback, is beyond the scope of this work.

2. Simulation model

The finite element (FE) software Abaqus [14] was used for conducting the numerical investigations. The simulation model was created within the Abaqus/CAE environment. Preprocessing operations included (i) generating the model geometry and the mesh, (ii) specifying the material properties, as well as (iii) defining the process parameters and boundary conditions. The FE analysis was finally performed with the Abaqus/Standard solver. Postprocessing operations including the visualization of the results were also performed using Abaqus/CAE.

2.1. Model geometry and mesh

Figure 2 (a) illustrates the main dimensions of industrial bending tools [15] which were used in this study for creating the two-dimensional (2D) symmetric model geometry shown in Figure 2 (b). The model included four parts: the punch, the V-shaped die, the insert, and the sheet to be bent. Each of these parts was treated as deformable to investigate possible deformations of the entire system during the bending process. They were meshed using four-node, bilinear, quadrilateral plane strain elements with reduced integration and hourglass control (“CPE4R” elements). In order to capture properly the local plastic deformation gradients the mesh was distinctly refined at the contact zones. Particularly in the zone between the sheet and the insert the nominal element size was just 0.02 mm.

Figure 2. (a) Bending tool dimensions, (b) meshed model geometry with local mesh refinement

2.2. Material properties

Experimental characterization of the material properties is strongly recommended since the results of the numerical simulations are distinctly influenced by the material data input. Therefore, the elastoplastic material properties of the sheet to be bent were determined by uniaxial tensile testing. The Young’s modulus and the flow curves were then calculated based on the stress-strain curves obtained for two different nominal strain rates, 0.002 s$^{-1}$ and 0.125 s$^{-1}$. Since the results were quite similar for
both strain rates, the investigated mild steel was identified to exhibit just slight rate dependence. The flow stresses within the distinct Lüders regime at plastic strains below 0.025 were approximated as constant. The Hockett-Sherby [16] relationship was applied for extrapolating the flow curves to plastic strains beyond 0.13. Figure 3 illustrates the obtained strain rate dependent flow curves of the mild steel sheet. In contrast to the sheet the bending tools (punch, die) and the die inserts should not be subjected to any macroscopic plastic deformation during the bending process. Hence, plastic material data were not required for modeling those parts. Table 1 summarizes both the elastic material properties and the densities which were mandatory for creating the numerical model.

Table 1. Elastic material properties and densities

| Part     | Sheet          | Tools          | Insert 1   | Insert 2   |
|----------|----------------|----------------|------------|------------|
| Material type | Mild steel     | High-grade steel | Thermoplastic | Thermoplastic |
| Designation     | S355J2+N  | 42CrMo4    | PXX         | PXXX        |
| Density         | 7850 kg/m³  | 7850 kg/m³ | 1300 kg/m³ | 1300 kg/m³ |
| Young’s modulus | 212 GPa     | 205 GPa     | 3.24 GPa   | 4.08 GPa   |
| Poisson’s ratio | 0.3          | 0.3          | 0.4        | 0.4        |

Figure 3. Flow curves of the steel sheet

Figure 4. Punch motion

2.3. Process parameters and boundary conditions

The bending cycle includes three sub-steps: (i) the downward motion of the punch, i.e. the bending stroke, (ii) a short dwell of the punch at the bottom dead center and (iii) the final upward motion of the punch, i.e. the reverse stroke. Figure 4 illustrates the motion of the punch during the bending cycle as considered in the current model. As marked in Figure 2 (b), vertical symmetry was applied to each of the parts. The bottom edge of the die was pinned to prevent translational motion in each direction. A uniform Coulomb friction coefficient of 0.30 was assigned in tangential direction to the surfaces being in contact with the comparatively rough sheet surface. However, since the inserts and the die exhibit smooth finished surfaces, the friction coefficient between these parts was reduced to 0.15. Table 2 summarizes the bending process parameters and the friction coefficients used in the numerical model.

Table 2. Bending process parameters and friction coefficients

| Parameter                      | Value |
|--------------------------------|-------|
| Punch velocity, bending stroke | 10 mm/s |
| Punch velocity, reverse stroke | 20 mm/s |
| Punch stroke                   | 10 mm  |
| Punch dwell at bottom dead center | 0.5 s   |
| Total time of the bending cycle | 2.0 s   |
| Coulomb friction coefficient, steel sheet / punch | 0.30 |
| Coulomb friction coefficient, die / insert | 0.15 |
3. Simulation results

The colors in Figure 5 represent the calculated equivalent plastic strain (“PEEQ”) inside the steel sheet. Obviously, bending of the sheet induces plastic deformation which is concentrated at the zone close to the punch tip, Figure 5 (a). However, plastic deformation also occurs locally at the zone close to the steel insert radius, Figure 5 (b). Though the plastic strain at the radius zone is comparatively small (just about 1/100 compared to the zone at the punch tip), it is sufficient for smoothing the roughness peaks at the sheet surface. This is identified as the main mechanism causing visible linear bending marks in three-point air bending. In comparison, using the thermoplastic insert (e.g. PXX) increases the width of the contact zone and therefore induces de facto no plastic deformation, Figure 5 (c).

![Figure 5. Equivalent plastic strain inside the steel sheet at the zones (a) close to the punch tip, (b) close to the steel insert radius and (c) close to the PXX insert radius](image)

Figure 6 (a) shows profiles of contact pressure (“CPRESS”) and friction shear stress (“CSHEAR”) at the surface of the steel sheet when using the steel insert and the thermoplastic die inserts, respectively. The profiles describe exemplarily the surface stresses occurring at the end of the bending stroke when the punch is located at the bottom dead center, as illustrated in Figure 5. Note that the constant stress ratio |CSHEAR|:CPRESS = 0.30 represents the predefined friction coefficient between the steel sheet and the insert. The stress peak shown in Figure 6 (a) is almost five times higher when using the steel insert instead of the thermoplastic inserts. That explains the plastic deformation which is illustrated in Figure 5 (b). Figure 6 (b) shows the equivalent plastic strain (“PEEQ”) at the surface of the steel sheet which is plotted as calculated along the overall contact zone width.

![Figure 6. (a) Contact pressure and friction shear stress, (b) equivalent plastic strain at the contact zone](image)
4. Experimental validation

In order to validate the results of the simulations, bending experiments on 2 mm thick mild steel sheets (S355J2+N) were performed using a TRUMPF TruBend 7036 bending machine and TRUMPF LASERdur bending tools (punch OW 320, die EV006), as schematically illustrated in Figure 2 (a). Two die inserts having the same geometry but made of different thermoplastics, PXX and PXXX, were used. Hence, the experimental setup was practically identical to the modeled configuration. The bending marks caused by the thermoplastic die inserts, Figure 7 (a) and (b), are significantly less pronounced compared to the distinct bending marks caused by the steel die, Figure 1 (c). The slight marks shown in Figure 7 were wiped off almost completely using a soft cloth and a cleaning fluid. Thus, these marks represent rather surface adhesions of abraded insert material and tiny dirt particles than surface imprints, though slight flattening of roughness peaks may also occur.

Figure 7. Reduction of bending marks when using thermoplastic die inserts: (a) PXX, (b) PXXX

Detailed microscopic investigations of the bending marks confirm the first macroscopic observations. Figure 8 compares micrographs as well as roughness profiles of bending marks caused (a) by the steel die and (b) by the thermoplastic die inserts, respectively. The micrographs and the roughness profiles were captured using the Alicona InfiniteFocus optical 3D measurement system. Obviously, the steel sheet exhibits an original surface roughness of about 10 µm. However, the roughness peaks are considerably smaller within the imprint zone shown in Figure 8 (a) which is clearly distinguishable from the adjacent unaffected sheet surface. In comparison, no noticeable flattening of the roughness peaks and therefore no imprints are detected at the zones shown in Figure 8 (b). Figure 9 provides a three-dimensional (3D) visualization of the imprint from Figure 8 (a). The colors represent differences in the topography height. It is obvious that flattening of the roughness peaks occurs in the imprint region where the topography differences are less pronounced.

Figure 8. Roughness of bending marks when using (a) the steel die and (b) thermoplastic die inserts

Figure 9. Three-dimensional visualization of the imprint topography
5. Conclusions and outlook

The current study investigates the basic mechanisms of bending mark formation at the contact zones in air bending of sheet metals by means of finite element simulations which are experimentally validated. The results demonstrate that the intensity of the bending marks depends strongly on the elastic properties of the tool surfaces which are in contact with the sheet to be bent. Tool materials of low stiffness, i.e. with low Young’s modulus, increase the width of the contact zone due to elastic deformation. This effect reduces the plastic strain in the sheet which is induced at the contact zones during the bending process. Accordingly, unfavorable imprints (bending marks) due to local plastic deformation of the sheet surface are significantly reduced. Regarding reduction or even almost prevention of bending marks the evaluated thermoplastic die inserts exhibit superior properties compared to the steel die.

However, it should be noted that thermoplastics have lower hardness compared to steel. Therefore, thermoplastics do not penetrate or scratch the surface of the steel sheet during the bending process, but their abrasive wear is still an open issue. For that reason, quantifying the specific wear resistance of thermoplastics particularly used for bending applications is an ongoing work.

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