Experimental and simulated comparison of finite element models of bimetallic sheets for deep drawing process

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Abstract
In this study, different techniques used for modelling of bimetallic sheets by finite element (FE) method have been compared. Sheets modelled with five different assumptions were compared with each other and experimental data to determine the FE model that gives the most realistic result. FE models were created with the assumption that the adhesion was excellent or separable and with the case that the solidified adhesive in the intermediate layer was modelled and not modelled. As a result, the closest values to the experimental results were obtained with the model created with the assumption that there is a solidified adhesive layer in the middle layer and there is an adhesion interface between this layer and metallic layers. On the other hand, when the adhesive is not modelled in the middle layer, it has been observed that the solution time is reduced by 2.6 times while small changes are seen in the results.

Keywords
bimetallic sheets • FEM • Deep drawing • Cohesive zone model • Columb friction

1 Introduction
Sheet metals are frequently used in products produced by deep drawing methods such as kitchen utensils, medical storage boxes and automobile bodies. In places where willing high-strength and lightness, multi-layer sheets are preferred instead of single sheets. Layered sheets are divided into 3 main groups as metal/metal, metal/polymer/metal and metal/composite/metal. Bimetallic sheets are layered sheets obtained by combining two different sheet metals with methods such as welding, bonding, rolling or hot pressing. By using different metals, a composite sheet has different properties, and thicknesses can be obtained with superior properties of each sheet. In this way, lighter, corrosion-resistant and high-strength materials can be obtained. It is especially preferred in sectors where material lightness is at the forefront for energy saving, such as the automotive industry.

Deep drawing is basically the process of drawing sheet metal into the die with the help of a punch. This manufacturing technique is a frequently used method in productions made with bimetallic sheets. However, problems such as separation between layers, wrinkling and tearing are encountered in products produced by this method. There are different studies in the literature investigating these problems. For example, Mori and Kurimoto [1] examined the formability and wrinkling behaviour of the sheets with the press-forming tests of pressure welded hot rolled stainless steel-aluminium sheets. As a result, they observed that the formability of the bimetallic sheet in stretching and deep drawing processes is better when the steel layer comes into contact with the punch. They also stated that the wrinkling state during deep drawing is controlled by the harder stainless steel. Chen et al. [2] investigated the earing behaviour of Al/Cu bimetallic sheet during cylindrical deep drawing. They bonded aluminium and copper sheets by cold rolling. Afterwards, they determined the level and change of earing by subjecting the sheets they annealed at different temperatures to a deep drawing process. Morovvati et al. [3] investigated the required blank holder force (BHF) to prevent wrinkling in deep drawing of an adhesive-bonded aluminium/steel bimetallic sheet. As a result, they showed that the BHF required to avoid wrinkling in the layered sheets...
consisting of high and low strength sheets is at a value between the BHF s required for each layer. In another study, Aghchai et al. [4] examined the effect of the mechanical properties of materials on the formability of Al3004/St12 bimetallic sheets. The proposed theoretical model showed that the forming limit curve (FLC) of the laminated sheet is between the FLCs of the constituent materials. Afshin and Kadkhodayan [5] investigated the effects of different factors such as temperature, grain size, BHF, layer alignment and friction on the deep drawing process of Al 1050/St 304 and Al 5052/St 304 bimetallic sheets. As a result, they determined that the damage occurred in the areas of the punch radius and cup walls. In addition, they found that the punch force was less if the steel layer was on the upper side than when the aluminium layer was on the upper side.

Finite element (FE) analysis is used to predict the problems encountered in deep drawing processes. Experiments in many studies have been supported by FE analysis. In the analysis of bimetallic sheets, it is essential to use the model that gives the most realistic result in the shortest time. Bimetallic sheets have been modelled with many different assumptions in the literature. Takuda et al. [6] simulated the deep drawing process of the St/Al bimetallic sheet. They neglected the resin layer in the FE model of the sheets and bonded with polyurethane resin. Therefore, the resin layer was not modelled, and it was accepted that there was no slippage between the layers. Parsa et al. [7] investigated numerically and experimentally the effect of thickness ratio and layer sequence on the drawing ratio that can be obtained in deep drawing of Al/St bimetallic sheets. They accepted that there is no slippage between layers in the models created axisymmetrically. Bagherzadeh et al. [8] modelled the hydro-mechanical deep drawing (HMDD) process of St/Al bimetallic sheets using the finite element method (FEM). St/Al bimetallic sheet was laminated by a polyurethane-based adhesive. Similar to previous studies, they modelled bimetallic sheets as two different layers, but made the assumption that there was no slippage between layers.

Marandi et al. [9] investigated the bulge test of Al/Cu bimetallic sheets using FEM and confirmed it by experimental test. Al/Cu bimetallic sheets were manufactured by the explosive welding method. They assumed that layers in the common interface were sticking firmly to each other, and any slip or separation did not occur between layers while subjecting stresses and deformation. In the light of this assumption, each layer was modelled separately, and then layers were bonded to each other with tie constraint. The simulation results of their study showed similarity with the experimental results. Sakhtemanian et al. [10] carried out the influences of some process parameters on bimetallic sheets’ incremental forming, such as layers’ arrangement, forming load and surface finish. Titanium and low-carbon steel sheets were connected by the explosive welding method. They validated the FE results using experimental data. In their study, the shell element was used for meshing the blank, and they assumed that the sheets were perfectly bonded. To simulate the bimetallic sheet, one section was defined for each layer, and the material properties of each sheet were attributed to each section. Then both sections were attached to each other using tie a constraint. Thereby, no slippage permitted between layers. Karajibani et al. [11] also used the same modelling method for Al/Cu bimetallic sheet. As in previous studies, they fabricated the bimetallic sheets using explosive welding.

Tseng et al. [12] experimentally investigated the formability of Al/Cu bimetallic sheets manufactured with roll bonding in different thickness ratios with FE simulation. In the models they created, the bimetallic sheet was modelled as a single sheet. In addition, they determined the material properties with the tensile tests made on the laminated sheets. In another study, Morovvati et al. [3] investigated the BHF required to prevent wrinkling in deep drawing of Al/St bimetallic sheet bonded with polyurethane adhesive. By modelling the polyurethane interlayer in the FE model of the sheets, they accepted that this layer adheres tightly to the aluminium and steel layers. There is no slippage and separation between the layers.

Nejad et al. [13] modelled the study, which was previously performed experimentally by Attrian and Fereshteh-Saniee [14], with the Abaqus finite element programme. After determining that the models were compatible with the experimental results, they analyzed the effects of punch radius, die radius, friction coefficients of steel and brass layers on surfaces, BHF and sheet diameter on punch force and thickness reduction statistically with the response surface method. While modelling bimetallic sheets, they accepted the presence of Columb friction between layers. Therefore, they created a model that allows sliding and separation between layers. They determined the average friction coefficient of steel and aluminium sheets as the friction coefficient between these two layers.

Liu and Xue [15] experimentally examined the formability of AA5052/polyethylene/AA5052 sandwich plates in their study. They prepared three kinds of AA5052/polyethylene/ AA5052 sandwich samples with different thicknesses of core material by hot pressing bonding method. Experimental FLC is compared with the results of FE analysis. In the FE model, all metal and polymer layers are modelled. The interlayer contact state is defined by the cohesive zone model (CZM). In later work, they examined the deep drawing behaviour of the same sheets. In their studies, which they supported with the FEM, they continued to use the CZM [16].

In this study, St/Al bimetallic sheets are modelled with the assumptions used in the above studies and different assumptions in addition to them, and the most suitable model type for bimetallic sheets is tried to be determined. For this purpose, T-peel test and single lap joint test were performed to determine the peel resistance and shear strength of the samples. These tests are modelled in the ABAQUS FE programme, and the CZM parameters are determined. Then, by using five different
models with the determined parameters, the behaviour of the bimetallic sheets in the deep drawing process was simulated. The simulation results are compared with the experimental results, and the optimum model type that gives the most realistic result in the shortest time is determined.

2 Material

In this study, steel and aluminium sheets were selected to create bimetallic sheets. A low-carbon cold-rolled steel sheet (DC01) suitable for deep drawing is used in the steel layer. This sheet metal is used in many places such as household items, refrigerators, washing machines, the automotive industry, office supplies and lighting equipment. In the aluminium layer, EN AW 5754 H111 aluminium-magnesium alloy sheet is used. This sheet has a harder structure than pure aluminium. Its corrosion resistance is high as well as welding ability is very good. In addition, it has high fatigue strength and is suitable for cold forming and coating. The chemical contents offered by the companies belonging to steel and aluminium sheets are given in Table 1.

Bimetallic sheets used in experiments are combined with polyurethane resin. The properties of the polyurethane resin offered by the company are given in Table 2. This adhesive can be used in different conditions and at different temperatures. It has high electrical resistance and dielectric coefficient. Also, it is resistant to abrasion, acid and similar corrosive substances. It hardens at low temperatures without significant volume change. Curing time can be shortened thanks to catalysts. In the preliminary tests with epoxy and other silicon-based adhesives, it was observed that these adhesives become brittle after curing. In the polyurethane resin, the structure formed after curing was ductile.

Mechanical properties of sheet metals and resin used in the study were determined by tensile testing. Steel and aluminium specimens are prepared according to ASTM-E8 standard in the direction of rolling, diagonal and perpendicular to the direction of rolling. Tensile tests were carried out on Instron 5982 universal test device with a loading capacity of 10 tons. The true stress-true strain curves of sheet metals are given in Fig. 1. In addition, the mechanical properties of sheet metals are given in Table 3.

In the study, the adhesive used for joining the sheets was poured into moulds prepared as dog-bone shape, and after being cured completely, they were subjected to tensile testing. The sizes of the produced specimens are the same as sheet metal specimens. The true stress-true strain curve of the polyurethane resin is presented in Fig. 2.

3 Methods

3.1 Bonding procedure

Steel and aluminium sheets were laminated by a two-component polyurethane resin. Before the process, the surfaces of the sheet metals were sanded with 180 grit sandpaper, and the surface was cleaned from oxide and similar residues. Then, the surface is wiped with ethyl alcohol and cleaned from dirt such as oil and left to dry. Next, polyurethane resin prepared by adding a hardener in a ratio of 4:1 was applied to the surfaces. The adhered samples were left to dry for 24 h.

3.2 Experimental equipment

Bimetallic sheets were deep drawn in a die set (Fig. 3a). The dimensions of the die set are given in Fig. 3b. A double-acting hydraulic press with a loading capacity of 80 tonnes was used for this process. The circular specimens with a diameter of 90 mm were deep drawn by adjusting the blank holder force (BHF) to 53 kN (~30 bar). During the process, punch force and displacement were recorded. Specimen thicknesses were measured after a deep drawing process.

4 Finite element models

4.1 Cohesive zone model

In sheets combined with bonding, the adhesive applied to the interface attaches to the surface by establishing a bond with

| Table 1 Chemical composition of steel and aluminium sheets |
|----------------------------------------------------------|
| Materials | %C | %P | %S | %Mn | %Si | %Mg | %Al | %Fe |
| EN 10130   | 0.12 | 0.045 | 0.045 | 0.6 | – | – | – | 99.16 |
| EN AW 5754 H111 | – | – | – | – | 0.42 | 3.16 | 96.42 | – |

| Table 2 Polyurethane resin adhesive properties |
|-----------------------------------------------|
| Properties | Value |
| Density of adhesive | 1.43 g/cm³ |
| Density of hardener | 1.22 g/cm³ |
| Temperature resistance | −45/+280 °C |
| Shore hardness | 90–95 |
| Dielectric coefficient | 3.5 F/m |
| Application temperature | 5–35 °C |
the sheet surface. Classical Columb friction is usually insufficient to define this situation. Because, different from the friction situation between the bimetallic sheets, the surfaces stick together. Adhesion has a different strength depending on peeling and sliding conditions, and when this strength is exceeded, the surfaces do not separate entirely and gradually damage occurs and continues.

In order to simulate the bimetallic structure, cohesive zone model (CZM) was used between the surfaces [17]. CZM uses the delamination that occurs against the tensile load to model the split on the interfaces. In other words, it takes into account the separation distance of the surfaces and the force applied to separate the adhered surfaces. Because the adhesive allows some elastic elongation, CZM accepts an elastic traction-separation law between surfaces before the damage. In case of exceeding this elastic limit, CZM assumes that the damage in the adhesive bond is caused by the gradual deterioration of the adhesive stiffness.

In the adhesive surface model, damage begins with a quadratic equation reaching the value “1”, which includes the adhesion stresses [18]. In Eq. 1, \( \sigma_1, \sigma_2, \sigma_3 \) show the stress in the normal, first, and second shear directions, respectively. \( \sigma_1^0, \sigma_2^0, \sigma_3^0 \) mean critical contact stresses in cases where the separation is only in the normal of the contact surface, only in the first, and only the second shear direction, respectively.

\[
\left\{ \frac{\sigma_1}{\sigma_1^0} \right\}^2 + \left\{ \frac{\sigma_2}{\sigma_2^0} \right\}^2 + \left\{ \frac{\sigma_3}{\sigma_3^0} \right\}^2 = 1
\]  

(1)

The equation stated above only represents the initiation of the damage. However, after the damage initiates, it develops progressively. An energy statement is used in CZM to express the progress of the damage. The fracture energy that will occur on the traction of adhering surfaces in both normal and cutting directions (mixed mode) can be defined by a power law. Thanks to this power law (Eq. 2), failure under mixed mode

| Property                  | DC01 | EN AW 5754 |
|---------------------------|------|-------------|
| Elastic modulus, \( E \) (GPa) | 194.7 | 77.03       |
| Yield stress, \( \sigma_{0.2} \) (MPa) | 204.3 | 120.2       |
| Tensile stress, \( \sigma_\varepsilon \) (MPa) | 335.9 | 237.5       |
| Uniform elongation, \( \varepsilon \) (mm/mm) | 0.241 | 0.188       |
| Max. elongation, \( \varepsilon_k \) (mm/mm) | 0.406 | 0.204       |
| Strain hardening exponent, \( n \) | 0.212 | 0.261       |
| Strength coefficient, \( K \) (MPa) | 576.3 | 436.9       |
| \( R_0 \) | 1.962 | 0.942       |
| \( R_{45} \) | 1.271 | 0.995       |
| \( R_{90} \) | 2.600 | 0.846       |
| Thickness, \( t \) (mm) | 0.5  | 1           |

![Fig. 1 True stress-true strain diagram of steel and aluminium sheets](image)

![Fig. 2 Stress-strain curve of polyurethane resin](image)
can be expressed as the sum of the energies required for failure caused by individual modes (normal or shear mode). In Eq. 2, \( G_1 \), \( G_2 \) and \( G_3 \) represent the Griffith fracture energy required for separation in the first, second shear and normal direction, respectively. \( G_1^C \), \( G_2^C \) and \( G_3^C \) express the critical fracture energies required for failure in the normal, first and second shear directions, respectively.

\[
\left\{ \frac{G_1}{G_1^C} \right\} + \left\{ \frac{G_2}{G_2^C} \right\} + \left\{ \frac{G_3}{G_3^C} \right\} = 1
\]  

(2)

Fig. 3  a The view of the hydraulic press and die set and b dimensions of the die set
In ABAQUS finite element programme, $\sigma_1^0$, $\sigma_2^0$, $\sigma_3^0$, $G_1^C$, $G_2^C$ and $G_3^C$ values must be given as input to model CZM. $\sigma_3^0$ and $G_3^C$ values, which are in the normal direction from these values, are determined by $T$-peel test and $\sigma_1^0$, $\sigma_2^0$, $G_1^C$ and $G_2^C$ values are in the shear direction and determined by single-effect connection test.

4.1.1 T-peel test model

$T$-peel test is a test performed to determine the strength of the adhesive in the surface normal direction [19]. The test sample is obtained by bonding two L-shaped sheet metal together with an adhesive to form a T-shape. This specimen is then tested by pulling it perpendicular to the adhesion surface. In this study, the experimental $T$-peeling test was modelled with the ABAQUS and the input parameters of the adhesion were determined. The adhesive behaviour between the two surfaces can be simulated by the CZM. The mechanical properties of the adhesive in the normal direction ($\sigma_3^0$ and $G_3^C$) were determined by the $T$-peel test.

$T$-peel test sample is given in Figure 4 a, and FE model is shown in Fig. 4 b. Aluminium is modelled on the upper layer, steel sheet on the lower layer and 02-mm-thick adhesive material on the intermediate layer. CZM is defined between the middle layer and metal surfaces (aluminium and steel sheets). CPE4R element type with four nodes is used for all elements in the model. The mesh size is kept too small (~ 0.1 mm) to provide a solution. Each layer has 3 layers of mesh throughout the thickness. The total number of mesh elements in the model is 5667. The loop in Fig. 5 has been used to determine the CZM parameters [20].

In Figure 6, simulation results obtained from FE model are compared with experimental data. According to the latest estimate made by the programme, the curve obtained was close to the experimental curve. Accordingly, the maximum stress required for the onset of damage in the normal direction was determined as 3.8 MPa. The energy needed to cause the failure is specified as 1000 J/m².

4.1.2 Single lap joint model

Single lap joint test is a standard test method using to determine the shear strength of adhesion [21]. Standard test specimen is given in Figure 7 a. The single lap joint test was modelled with FEM (Fig. 7b). A 4-node CPE4R element type was used in the model. Mesh size is 0.05 mm, and the model has 673 mesh elements. CZM parameters in the shear directions were determined by using the same loop as the $T$-peel.

Experimental and FEM results of the single lap joint test are given in Figure 8. The maximum stress value that gives the closest output to the experimental data is 3.2 MPa and fracture energy value is 820 J/m². CZM parameters estimated by FEM are given in Table 4.

4.2 Bimetallic sheet models

In bimetallic sheets, two different metallic materials are combined with an adhesive. The adhesive applied to the sheet metal surface solidifies after the process, and adhesion occurs between the solidified adhesive and the sheet metal. From this point, FE models of bimetallic sheets can be modelled by making different assumptions. In Figure 9, five different models used in FE analysis of bimetallic sheets formed by bonding are given.

**Model-A** This model is the closest model to the real situation. The adhesive that solidifies between the sheet metal is considered a separate layer. CZM is defined between this layer and the sheet metal surface (Fig. 9a). If the adhesion force is exceeded during forming, separation may occur between the
layers. In some studies in the literature, layered sheets are modelled in this way [16, 18].

**Model-B** In this model, it is accepted that there is an excellent adhesion between sheet metal and solidified adhesive (Fig. 9b). The sheet metal is considered as a whole and is split into three parts to identify different materials. No contact condition has been defined on the interface. No separation is observed during forming.

**Model-C** In this model, CZM is defined between sheet metals (Fig. 9c). The solidified adhesive is not modelled as a layer. If the adhesion force is exceeded during forming, separation may occur between the surfaces.

**Model-D** In this model, adhesion is assumed to be perfect (Fig. 9d). The adhesive between sheet metals has been neglected. Sheets are modelled as in Model-B, but the middle layer is not modelled. No contact condition has been identified on the interface.
interface. No separation is observed during forming. Bagherzadeh et al. [8] and Atrian and Fereshteh-Saniee [14] modelled the layered sheets in this way.

**Model-E** This model is modelled similarly to Model-C (Fig. 9e). However, Columb friction is defined between layers instead of CZM [13]. As the coefficient of friction between steel and aluminium sheets, the average value of the friction coefficients between sheets and dies was used. There may be slippage and separation between layers during forming.

Different models used in simulations were summarized in Table 5. Deep drawing simulations were carried out with the different models described above. By comparing the results obtained from these models with the experimental results, the model that gives the most realistic result was determined.
4.3 Modelling of deep drawing process

ABAQUS/Explicit was used for the simulation of the deep drawing process. FE models of die set were created with exact dimensions as the die set used in experiments. Since Al and St sheets have planar anisotropy, 1/4 of the model was designed. Symmetric boundary conditions on the X and Y axes are defined. The punch (Figure 10a), blank holder (Fig. 10b) and die (Fig. 10c) were modelled as rigid elements with element type R3D4. Five different sheet metal models were created for each simulation, as stated in the previous section and

![FE models and schematic view of bimetallic sheets](image)

**Table 4** CZM parameters

| $\sigma_1^0$ | $\sigma_2^0$ | $\sigma_3^0$ | $G_1^C$ | $G_2^C$ | $G_3^C$ |
|--------------|--------------|--------------|--------|--------|--------|
| 3.2 MPa      | 3.2 MPa      | 3.8 MPa      | 820 J/m² | 820 J/m² | 1000 J/m² |

**Table 5** Summary of the created models

| Model | CZM | Adhesive layer | Friction between layers | Separation |
|-------|-----|----------------|-------------------------|------------|
| A     | Yes | Yes           | No                      | Allowed    |
| B     | No  | Yes           | No                      | Not allowed|
| C     | Yes | No            | No                      | Allowed    |
| D     | No  | No            | No                      | Not allowed|
| E     | No  | No            | Yes                     | Allowed    |

Fig. 9 FE models and schematic view of bimetallic sheets: a Model-A, b Model-B, c Model-C, d Model-D and e Model-E
the deformable element type (C3D8R) was chosen for sheet metal. The assembly of the model can be seen in Fig. 10.

The deep drawing process is a quasi-static operation. Therefore, step time should be long enough to eliminate inertia force and short enough for a quick solution. For this reason, the shortest step time is determined by performing frequency analysis on the sheet metal. The frequency analysis shows that the Al and St blanks have a fundamental frequency of 1124.8 Hz and 548.5 Hz, respectively. These frequency values correspond to a period of 0.00089 s for Al and 0.0018 s for St blank. Accordingly, the appropriate step time

| Materials | Die  | Punch | Blank holder |
|-----------|------|-------|--------------|
| Al        | 0.0007 | 0.008 | 0.005        |
| St        | 0.09  | 0.1   | 0.1          |

Fig. 10 Finite element model of deep drawing process: a Punch, b blank holder, c die and d assembled die set

Fig. 11 Thickness measurement points on deep drawn bimetallic sample
to cover all models was determined as 0.002 s. It should be determined whether or not the solution is quasi-static for this time step. One good approach is to compare the kinetic energy history to the internal energy history [17]. To determine whether an acceptable quasi-static solution has been obtained, the kinetic energy of the blank should be lower than 5% of its internal energy. When the results of the analysis with the selected step time were examined, the ratio of kinetic energy to internal energy was found to be 1.47%. Therefore, the step time specified as 0.002 s was accepted as a sufficient time for quasi-static analysis.

The mesh size of the deformable parts was determined by the optimization procedure. Different mesh sizes from 2 to 0.25 mm were created for Al, St and the solidified adhesive layer. Then, the thickness strain was compared after simulations with different mesh sizes. The simulation results show that mesh sizes smaller than 0.75 mm do not change the thickness strain but cause a rapid increase in solution time. Therefore, the optimum mesh size was chosen as 0.75 mm for all simulations.

The friction coefficients between the blank and the other die parts were set with a trial-error method. While the materials are successfully deep drawn to a specific blank holder force (BHF) in the experiments, they are damaged at the compression force above this value. In the simulations, a frictionless model was created initially. With this model, the maximum sheet diameters that can be deep drawn under the maximum BHF are determined. Then, the friction coefficient was added to this model, and the friction coefficients were changed until the same results were obtained with the experimental results. The friction coefficients obtained as a result of different trials are given in Table 6. In the experiments, in addition to the lubrication of the die surfaces and the sheet metal, a thin nylon layer was placed between the sheet metal and the die surfaces during the process, thus minimizing friction and obtaining successful deep drawing products. In the simulations, the low friction coefficient between the aluminium layer and the die surfaces is in agreement with the experimental results.

5 Results and discussion

5.1 Thickness strain distribution

Thickness measurements were made at six different points on the test sample (Figure 11), and the curve graph through these

| Model   | Slope  | Determination coefficient |
|---------|--------|---------------------------|
| Model-A | 1.061  | 0.9825                    |
| Model-B | 0.9457 | 0.9309                    |
| Model-C | 1.0513 | 0.9757                    |
| Model-D | 0.7578 | 0.9325                    |
| Model-E | 1.2056 | 0.9846                    |
points was drawn. In simulations made with Model-A, Model-B, Model-C, Model-D and Model-E, the thickness change in the aluminium layer was compared with the experimental results (Fig. 12). In the simulation results, the change in thickness across the section is given. It was observed that the thickness became thinner at the base of the cup (0–15 mm). This thinning has increased in the area of the punch radius. It has been determined that the thickness of the cup wall increases with distance from the punch radius.

In Figure 12, it can be seen that the thickness changes of Model-A and Model-C are similar. On the other hand, a similarity was observed in thickness changes between Model-B and Model-D. In the punch radius section (15–25 mm), all models show similar thickness changes, while the models show two different trends in the cup walls. Model-B and Model-D are significantly thinning from the punch radius to the middle of the cup wall, while Model-A, Model-C and Model-D begin to thicken along with the mug height after some thinning. The common feature of these three models is that sliding and separation between layers are allowed. This prevented the excessive thinning of the cup walls.

The results obtained from the aluminium layer of the test sample are matched with the results from the same points in the simulation (Figure 13). Experimental data and simulation data were transferred to a graph and the trend lines fitted to this data. The slope of the fitted lines and the determination coefficients of the lines have been given in Table 7. As the slope of the line close to 1, the similarity between the experimental results and the simulation results increases. However, the slope of the line is not enough. The determination coefficient shows how close the points are to the line. In other words, it shows how the line is compatible with the data. Therefore, as the determination coefficient close to 1, the accuracy of the simulation results will increase. It is seen in Fig. 13 that the highest determination coefficient is in Model-A. In addition, it has been observed that the slope value of the line fitted to Model-A is close to 1. On the other hand, although Model-C has similar results with Model-A, the determination coefficient of Model-C is lower.

In Figure 14, the thickness changes in the steel layer of the bimetallic sheet are compared with the thickness changes of
the test sample. While the thickness decreased at the bottom of the cup, the thinning increased in the starting and ending (20–30 mm) parts of the punch radius. It was observed that sheet metal thickened on the walls of the mug with increasing cup height. Unlike the aluminium layer, a significant thinning was detected at the end of the punch radius in the test sample. Since the steel layer remains above the neutral axis, the thinning in this region is more than aluminium.

The differences between FEM models for the steel layer are more pronounced in terms of thickness variation. Model-A and Model-C have similar curves, while Model-B and Model-D have similar curves. On the other hand, Model-E is similar to Model-A and Model-C in the punch radius area, and Model-B and Model-D at the cup walls. In Fig. 15, the thickness changes taken in the steel layer of the test sample and the results obtained from the simulations were given comparatively. The slopes of the trend lines and their determination coefficients were given in Table 8. It can be seen from the determination coefficients that the data are generally dispersed. The highest determination coefficient was obtained with Model-A. Although Model-B and Model-D slopes are close to 1, determination coefficients remained quite low. On the other hand, although Model-C’s slope is higher, the coefficient of determination remained lower than Model-A. Model-E is the model with the lowest slope and determination coefficient.

It is seen that the thickness variations are more in Model-B and Model-D in both layers. Because in these models, sliding and separation between layers were not allowed. Since there is no slipping between the surfaces, both layers move together and elongate equally during the deep drawing process. These elongations on the plane cause more deformation in the direction of thickness according to the constant volume rule. Since sliding between layers is possible in models created with CZM, the steel layer becomes thinner and flows into the die. This situation is already evident from the earing situations after the procedure. While there are different ear heights between the layers in models created with CZM, in other models, the ears are equal in both layers.

### 5.2 Punch force

Force-displacement curves during deep drawing were given in Fig. 16. The simulation results made with five different models are similar. Error rates between maximum punch forces were given in Table 9. Accordingly, although the experimental punch force curve was verified with all models, the lowest error rate for the maximum punch force was obtained with Model-C. However, other models have produced similar results. Some fluctuations occur in the punch force values in the simulation results. The cause of the fluctuation in the

**Table 8** Slope and determination coefficient of trend lines of St layer

| Model   | Slope   | Determination coefficient |
|---------|---------|---------------------------|
| Model-A | 0.8201  | 0.8351                    |
| Model-B | 1.0154  | 0.6986                    |
| Model-C | 0.8262  | 0.7306                    |
| Model-D | 1.0577  | 0.8016                    |
| Model-E | 0.6936  | 0.6333                    |

**Table 9** Max. punch forces and error ratio

| Model   | Max. punch force (kN) | Error |
|---------|-----------------------|-------|
| Model-A | 60.5                  | 10%   |
| Model-B | 62.3                  | 14%   |
| Model-C | 58.9                  | 8%    |
| Model-D | 59.7                  | 6%    |
| Model-E | 58.0                  | 9%    |
| Experimental | 54.7 ±1 | -     |

**Fig. 16** Comparison of punch forces obtained from deep drawing simulations with Model-A, Model-B, Model-C, Model-D and Mode-E with experimental punch force

**Fig. 17** Solution times of different models
punch force-displacement curve observed in the simulation is
the oscillation of the nodes in contact with the punch.

5.3 Solution times

Solution time for each of the simulations performed with dif-
ferent models was given in Fig. 17. These values were obtain-
ed with a PC with Intel Core i7-4930K CPU 3.40 GHz and
32 GB RAM. While the solution time for Model-B and
Model-D is around 8 min, this value is around 32 min for
Model-A. In other words, while a fast solution is obtained
with Model-B and Model-D, Model-A has taken about 4 times
more time to reach a solution. On the other hand, it can be seen
that the solution time of Model C and Model E is
around 12 min. Model C is the optimum model type
to obtain a fast and realistic solution considering the
thickness changes and solution times.

5.4 Equivalent strain distribution of different models

The equivalent strain distribution of different models after
deep drawing is given in Figure 18. The strain distribution
of all models except Model E is generally the same. In models
with solidified adhesive in the intermediate layer, Model-A
and Model-B, it is seen that the highest strain value is on
adhesive. Due to low strength and elastic structure of the ad-
hesive, the most strain occurs in this region. Earing is seen in
Model-A, Model-B, Model-C and Model-D. On the other
hand, in model E, earing occurs in the steel layer but not in
the aluminium layer. According to calculations after the ten-
sile tests, while aluminium has a low anisotropy coefficient in
single sheets, the steel sheet has a higher anisotropy coeffi-
cient. Accordingly, since only friction is defined between
layers in Model E, layers slipped on each other and layers
did not interfere with other layers during forming. In other
four models, due to the strong adhesion between the layers,
the aluminium layer and steel layer moved together,
resulting in a similar earing profile in both layers. It
has been observed that in the case of high adhesion in
bimetallic sheets, a lower earing height was obtained
compared to the monolithic steel sheet.

5.5 The effect of solidified adhesive thickness

The effect of the adhesive between the layers on the
thickness of the sheet during deep drawing has been
investigated. For this purpose, in addition to Model-A
and Model-C, simulations were made for 0.4- and 0.6-
mm adhesive thicknesses and thickness changes were
analyzed. Thickness changes in Al and St layers are
given in Fig. 19. The increase in the thickness of the
adhesive generally had no effect on the change in thick-
ness of the Al layer. On the other hand, when the St
layer is analyzed, it can be seen that the thickness of

![Fig. 18 Equivalent strain distribution on deep drawn cups](image1)

![Fig. 19 Strain distributions for different adhesive thickness: a Al layer and b St layer](image2)
the cup walls decreases with the increasing adhesive thickness. The causation of this is that the outer diameter of the cup increases with the increase of total sheet thickness and therefore more deformation in the outer layer.

6 Conclusion

In this study, the most accurate model was determined by comparing different simulation models used for bimetallic sheets. Within the scope of the study, five different models were created, and outputs such as thickness strain, punch force and solution time were presented comparatively. Major conclusions are as follows:

- The most realistic models were determined as Model-A and Model-C according to thickness strain. In both models, interlayer adhesion was defined by CZM.
- Although Model-A and Model-C gave similar results, the solution time required for Model-A was 2.6 times longer than that of Model-C.
- The maximum punch force was determined as 54.7 kN in the experiments. Model E and Model-C predicted the closest result with 6% and 8% error, respectively.
- The sheet metal in the outer layer becomes thinner due to the increase in the diameter of the cup if the adhesive thickness is more than 0.4 mm. However, the solidified adhesive does not need to be modelled as a separate layer in bimetallic sheets with a thin adhesive layer (<0.4 mm). In other words, bimetallic sheets with a thin adhesive layer can be modelled with Model-C.

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Data availability The authors shared all data and materials in manuscript.

Code availability Code available and can be share if necessary.

Declarations

Conflict of interest The authors declare no competing interests.

References

1. Mori T, Kurimoto S (1996) Press-formability of stainless steel and aluminum clad sheet. J Mater Process Technol 56:242–253
2. Chen C-Y, Kuo J-C, Chen H-L, Hwang W-S (2006) Experimental investigation on earing behavior of aluminum/copper bimetal sheet. Mater Trans 47:2434–2443. https://doi.org/10.2320/matertrans.47.2434
3. Morovvati MR, Fatemi A, Sadighi M (2011) Experimental and finite element investigation on wrinkling of circular single layer and two-layer sheet metals in deep drawing process. Int J Adv Manuf Technol 54:113–121
4. Aghchai AJ, Shakeri M, Dariani BM (2013) Influences of material properties of components on formability of two-layer metallic sheets. Int J Adv Manuf Technol 66:809–823
5. Afshin E, Kadkhodayan M (2015) An experimental investigation into the warm deep-drawing process on laminated sheets under various grain sizes. Mater Des 87:25–35. https://doi.org/10.1016/j.matdes.2015.07.061
6. Takuda H, Mori K, Fujimoto H, Hatta N (1996) Prediction of forming limit in deep drawing of Fe/Al laminated composite sheets using ductile fracture criterion. J Mater Process Technol 60:291–296
7. Parsa MH, Yamaguchi K, Takakura N (2001) Redrawing analysis of aluminum–stainless-steel laminated sheet using FEM simulations and experiments. Int J Mech Sci 43:2331–2347. https://doi.org/10.1016/S0020-7403(01)00038-8
8. Bagherzadeh S, Mirmia MJ, Mollaei Dariani B (2015) Numerical and experimental investigations of hydro-mechanical deep drawing process of laminated aluminum/steel sheets. J Manuf Process 18:131–140. https://doi.org/10.1016/j.jmapro.2015.03.004
9. Marandi FA, Jabbari AH, Sedighi M, Hashemi R (2016) An experimental, analytical, and numerical investigation of hydstatic bulge test in two-layer Al–Cu Sheets. J Mater Sci Eng 139:031005. https://doi.org/10.1115/1.4034717
10. Sakhtemanian MR, Honarpisheh M, Amini S (2017) Numerical and experimental study on the layer arrangement in the incremental forming process of explosive-welded low-carbon steel/CP-titanium bimetal sheet. Int J Adv Manuf Technol 95:3781–3796. https://doi.org/10.1007/s00170-017-1462-z
11. Karajibani E, Hashemi R, Sedighi M (2017) Forming limit diagram of aluminum-copper two-layer sheets: numerical simulations and experimental verifications. Int J Adv Manuf Technol 90:2713–2722. https://doi.org/10.1007/s00170-016-9585-1
12. Tseng H-C, Hung C, Huang C-C (2010) An analysis of the formability of aluminum/copper clad metals with different thicknesses by the finite element method and experiment. Int J Adv Manuf Technol 49:1029–1036
13. Hasan Nejad SJ, Hasanzadeh R, Domiavi A, Modanloo V (2017) Finite element simulation analysis of laminated sheets in deep drawing process using response surface method. Int J Adv Manuf Technol 93:3245–3259. https://doi.org/10.1007/s00170-017-0780-5
14. Atian A, Ferehshteh-Sancie F (2013) Deep drawing process of steel/brass laminated sheets. Compos Part B Eng 47:75–81. https://doi.org/10.1016/j.compositesb.2012.10.023
15. Liu J, Xue W (2013) Formability of AA5052/polyethylene/AA5052 sandwich sheets. Trans Nonferrous Metals Soc China 23:964–969. https://doi.org/10.1016/S1003-6326(13)62553-4
16. Liu J, Zhuang L (2018) Cylindrical cup-drawing characteristics of aluminum-polymer sandwich sheet. Int J Adv Manuf Technol 97:1885–1896
17. Abaqus Manual (2007) Abaqus/explicit: user’s examples and theory manuals. Dassault Systemes
18. Liu J, Liu W, Xue W (2013) Forming limit diagram prediction of AA5052/polyethylene/AA5052 sandwich sheets. Mater Des 46: 112–120. https://doi.org/10.1016/j.matdes.2012.09.057

19. ASTM D1876-08 (2015) Standard Test Method for Peel Resistance of Adhesives (T-Peel Test), ASTM International, West Conshohocken, PA. www.astm.org

20. Papazafeiropoulos G, Muñiz-Calvente M, Martínez-Pañeda E (2017) Abaqus2Matlab: A suitable tool for finite element post-processing. Adv Eng Softw 105:9–16. https://doi.org/10.1016/J.ADVENGSOFT.2017.01.006

21. ASTM D1002-10 (2010) Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal), ASTM International, West Conshohocken, PA. www.astm.org

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