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DYNAMIC ANALYSIS OF HANDLING COMPLIANT SHEET-METAL BLANKS

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ABSTRACT

Automating material handling of flexible sheet-metal blanks in stamping process requires attention due to its significant impact on product quality and productivity. This paper investigated the capability of a fully dynamic and nonlinear finite element technique in developing virtual material handling process of compliant sheet-metal blanks subject to time varying movability conditions. The technique used explicit time integration to avoid the formulation of stiffness matrix by a direct integration of the equations of motion. The influence of holding end-effector layout scheme and movability conditions on the final part quality was investigated.

INTRODUCTION

An integrated transfer press, complete with automated die change, coil and/or blank handling, and part exit automation, is a proven way to achieve maximized throughput potential from a single press. The automatic handling system is the link between the press units and significantly influences the flow of the entire process. The transfer mechanism moves the sheet-metal blank from one die station to the next. All blanks within the press are moved at the same time by a handling system attached to transfer rails, with a clamp, lift, and transfer sequence or merely a clamp and transfer sequence. A typical transfer press and its sheet-metal handling system are shown in fig. 1 [1].

The sheet-metal blanks must be grasped by an end-effecter, lifted, moved, and positioned between die stations. Researchers have identified the handling of compliant sheet-metal as one major cause of part dimensional variation [2-4]. The compliance of large sheet-metal blanks can cause (1) their permanent deformation during handling which further induces part dimensional variation, (2) a positioning error between die stations, i.e., the parts might lose their position and orientation accuracy prior to being placed in the next die station, and (3) a safety issue as the fluctuated deformation on the sheet-metal edges during handling might interfere with operator or other equipment. When the blank loses its positioning accuracy, the operation cannot stamp a good part. The part position or location error is quantified by the displacement of response points on the part surface or edges.

The task of material handling analyses is similar to fixturing analyses in terms of the holding end-effecter layout scheme. In analyzing the fixturing stability, several literatures apply the kinematic analysis and force closure which treats the workpiece as a rigid body. Although the kinematic analysis reduces the computation in fixturing analysis, this approach is not appropriate for a compliant workpiece. To model the compliant workpiece within the fixture, Finite Element (FE) has been applied by many researchers, such as [5-8]. Due to modeling complexity, most of the pure FE approaches are limited to static (time independent) external loads. Mittal [9] used multibody dynamics software to model the fixture-workpiece system subject to dynamic (time dependent) external loads; however the workpiece was simulated as a rigid body. To overcome the above shortcoming, Liao [10] formulated a flexible multibody dynamic model, which combines the advantages of FE to model the compliant workpiece and nonlinear rigid body dynamics to simulate the time dependent loads. The flexibility of sheet-metal is represented by modal coordinates of Craig-Bampton mode sets using implicit FE [11]. The tedious procedure of integrating two computer codes (FE and multibody dynamics) is a major drawback. Another inadequacy is that only displacement contours on the sheet-metal part can be predicted, meaning the stress distribution is not available from the simulation.

This paper investigated the capability of a fully dynamic and nonlinear finite element technique in developing virtual material handling processes for compliant sheet-metal blanks subject to time varying movability conditions. The explicit time integration avoids the formulation of a stiffness matrix by direct integration of the equations of motion. The influence of the holding end-effector layout scheme and movability conditions on the final part quality was investigated.

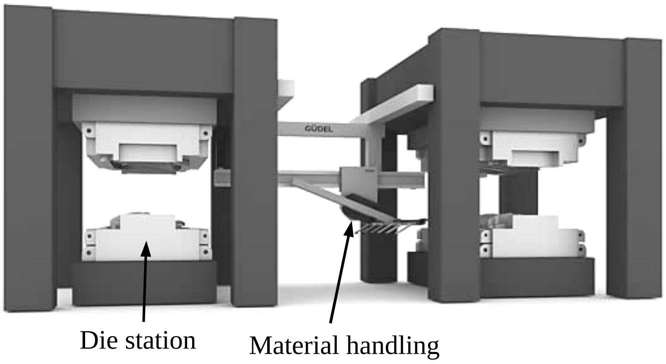


Fig. 1: A typical transfer press and its sheet-metal handling system [1]

ANALYSIS MODEL

In this study, the compliant sheet-metal part was modeled by finite element. Since transfer and holding mechanisms in handling systems are much stiffer than the sheet-metal part, the transfer frames and holding mechanisms are treated as rigid bodies. Therefore, the deformation due to external loads is fully distributed to the body of the sheet-metal. LsDyna [12] is used in this study to perform the FE work and create the compliant sheet-metal model along with movability conditions. LsDyna applies an explicit time integration method that avoids the formulation of a stiffness matrix and therefore reduces the cost per time step in solving high frequency response problems. A pre- and post-processing software ETA VPG [13] is used to manage the simulation results.

Both implicit and explicit time integration are used to compute the numerical solutions. The implicit method iterates until convergence, or equilibrium is reached for each time step. Then stiffness matrix is reformed/updated and inverted; meaning it requires a linear solver to invert the stiffness matrix. Cost per time step is very high particularly for nonlinear problems. The implicit time integration is typically used in low rate dynamic or quasi-static problems. In contrast to the implicit method, the explicit time integration method is particularly well-suited to nonlinear, high rate dynamic problems. In the explicit method, the equation of motion is advanced one time step at a time by using the central difference time integration scheme that updates the geometry by adding the incremental displacements to the initial geometry.

There are two types of material handling end effecters commonly used in the handling of sheet-metal parts in stamping line: finger grippers and suction cups. Finger grippers are usually used to transfer small and rigid parts and they are ideal for gripping parts that are difficult to grip using suction cups. The suction cups hold on to an object since the pressure under the cup is less than the external environment. Suction cup is used for a number of reasons: (1) it leaves no marks and causes no damage to sheet-metal surfaces, and (2) the gripping with vacuum can be accomplished from one single plane (only one side surface of the sheet-metal being moved) that makes handling easier. The cups range in diameter from 32 to 128 mm and are characterized by a tire-like tread design on the contact surface. Figure 2 shows typical suction cups with the rails. The suction cups will be utilized in this study.

The friction is considered in the contact areas between suction cups and sheet-metal part, as well as between the sheet-metal part and die. The friction in LsDyna is based on a Coulomb formulation and the frictional force resulting from contact interaction is modeled using a unilateral constraint between three-dimensional geometries [14]. The unilateral constraint means: a force that has zero value when no penetration exists between the specified geometries, and a force that has a positive value when penetration exists between two geometries. Preload suction force, gravity, and transferring acceleration/deceleration are the external loads to the material handling system.

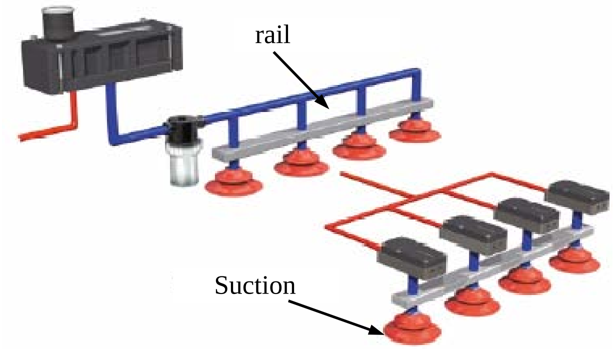


Fig. 2: Suction cups with the rails in sheet-metal handling system

APPLICATION EXAMPLE

An automotive roof sheet-metal blank (with the size of 1080 mm x 1080 mm) gripped by suction cups, as shown in fig. 3, is used to dynamically analyze the influence of suction cups placements on the accuracy of a compliant sheet-metal, as well as to estimate the deformation of the sheet-metal blank subjected to time-varying part movability conditions. The handling system has a clamp, lift, transfer, and placing sequence which refers to a 3-axis material handling operation.

The sheet-metal blank is modeled in FE (material: stainless steel S30200, E = 207,000 MPa; yield strength = 205 MPa; ultimate tensile strength = 515 MPa; Poisson ratio = 0.33; thickness = 1.08 mm). The sheet-metal model consists of 1020 plane strain quadrilateral elements. The suction cups and transfer mechanism are represented as rigid bodies. The LsDyna surface-to-surface contact is modeled between suction cups and sheet-metal part, as well as between the sheet-metal part and die. The transfer conditions are set as: (1) lift 400 mm distance (positive z-direction) with an acceleration of 5140 mm/s^2 (0.52*g*) reaching at the top speed of 700 mm/s and then with the deceleration of 4460 mm/s^2 (0.45*g*) reducing to zero speed in z-direction; (2) transfer 4005 mm distance in x-direction with the acceleration of 5500 mm/s^2 (0.56*g*) to reach a top speed of 1350 mm/s and then with the deceleration of 5600 mm/s^2 (0.57*g*) reducing to zero speed in x-direction; and (3) lower down 385 mm distance (negative z-direction) at the top speed of 257 mm/s (with the same acceleration and deceleration as the lifting operation). The 16-cup layout is shown in fig. 3. Figure 4 shows the velocity and acceleration curves in lifting operation.

As previously stated, the large deformation on sheet-metal edges during handling is a safety issue since these fluctuated edges might interfere with operator or other equipment. In addition, the final deformations (before the sheet-metal is completely settled in the next die station) on the critical points cause the sheet-metal positional error within the die station. The part position or location error is quantified by the displacements of response points on the part surface or edges. To measure the positioning error of the sheet-metal part before it is placed in the next die station, nine check points are selected at the front edge, central area and rear edge as illustrated in fig. 3. The stop pins or locators in a press die are generally placed on the edges of sheet-metal blank; hence the check points are selected along the perimeter of the blank. Any large deformations/displacements at these check points indicates that the sheet-metal loses its positioning accuracy.

SIMULATION RESULTS

Using the gripping and transfer conditions described above, the nodal point deformations on nine check points in the x, y, and z directions are obtained. The x-, y-, and z-direction are respectively defined in the transfer, lateral, and vertical or opposite of the gravity direction on the workpiece. Figures 5, 6 and 7 respectively show the simulated deformations of check points at the front edge, central area, and rear edge for the 16 cups layout. The simulated deformations are evaluated based on a local coordinate which is tied with the sheet-metal panel during the entire handling stage. Therefore theses simulated deformations are the values related to the undeformed panel, meaning the rigid body motions are excluded. The simulation results indicate there is no considerable large deformation during the handling (transferring stages shown in figs. 5, 6 and 7), which is less than 1 mm in the x and y directions and maximum 15 mm in the z direction. Although no large deformation (or permanent deformation) occurs during the handling, the final panel displacement/deformation (positioning stages shown in figs. 5, 6 and 7) that causes positional error is a quality issue in this case.

Table 1 summarizes the simulation results of final deformations at nine check points, i.e., the nodal point displacements at the end of simulations. The final deformations are the data at the end of positioning stages illustrated in figs. 5, 6 and 7. These final deformations are induced by gravity and contact effects as the suction cups release and place the panel into the die station. The final deformation in the x direction (less than 2.5 mm) will not cause positional error of the panel. However, the final deformation in the y and z directions might cause positional error, particularly in check points R2 (164 mm in z direction) and R3 (58 mm in y direction). Figure 8 shows the von-Mises stress distribution on the deformed sheet-metal (within a 16-cup scheme) in several time steps during transfer. The largest stress occurs at 183 MPa as the sheet-metal is lifted and lowered down to contact with the die.

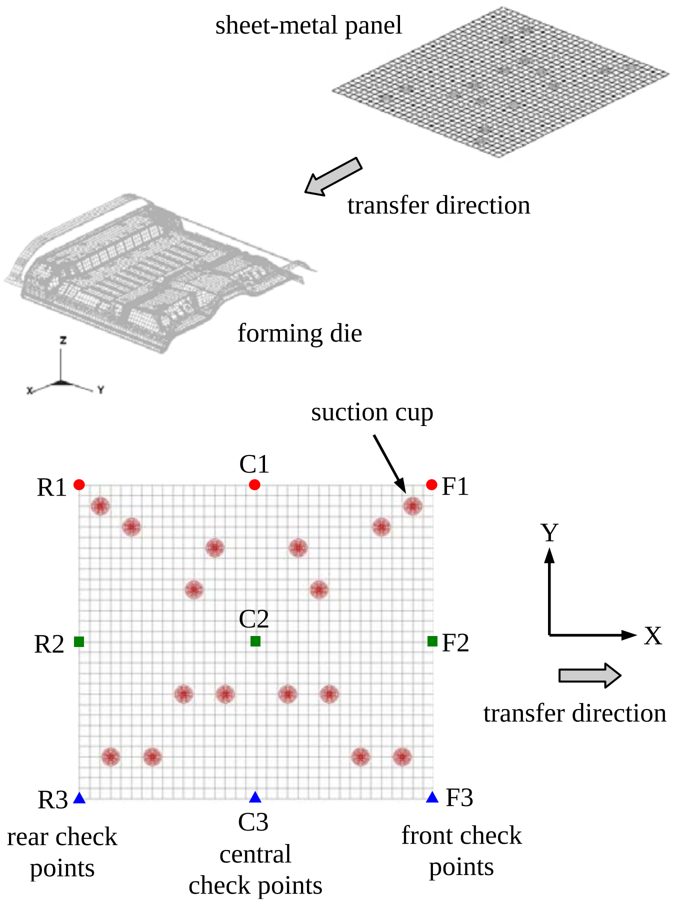


Fig. 3: Layout of suction cups and check points

The large deformation in the Y and Z axes was primarily due to modeling: (1) the suction cups and transfer mechanisms were treated as rigid bodies; (2) the suction pressure in the vacuum cups was assumed fully sustainable during the handling; and (3) the damping coefficient of the entire handling system was difficult to determine. Although the predictions were not validated with the corresponding panel, this study has investigated the capability of a fully dynamic and nonlinear FE technique in developing virtual material handling process of compliant sheet-metal parts.

CONCLUSIONS

Transfer press operation is a major process for stamping large sheet-metal parts. Transfer mechanism uses vacuum suction cups or finger type grippers to move the sheet-metal panel from one die station to the next. The resultant positioning error and permanent deformation on sheet-metal during handling process occurs in the transfer press and has been identified as one major cause of part dimensional variation. In addition, the large deformation on sheet-metal edges during handling is a safety issue since these fluctuated edges might interfere with operator or other equipment.

A fully flexible dynamic model was formulated to incorporate the motion condition using nonlinear and explicit FE technique. The explicit time integration avoids the formulation of huge stiffness matrix by a direct integration of the equations of motion. This technique takes material nonlinearities and failure, contact with friction, and high frequency response into account. The benefits include accurate modeling due to high mesh resolution, low cost per time step, and stress recovery (stress distribution contours) of the compliant sheet-metal part. The influence of holding end-effecter layout and movability conditions on the final part quality is investigated in the project.

This paper presented an analytical tool in design and analysis of suction cup holding mechanism for compliant sheet-metal blank in transfer press. The study needs experiments to validate the proposal model. The further study will integrate the developed model with optimization algorithm to determine the optimal number and locations of suction cups such that the sheet-metal deformation will be minimized as it is positioned in die station.

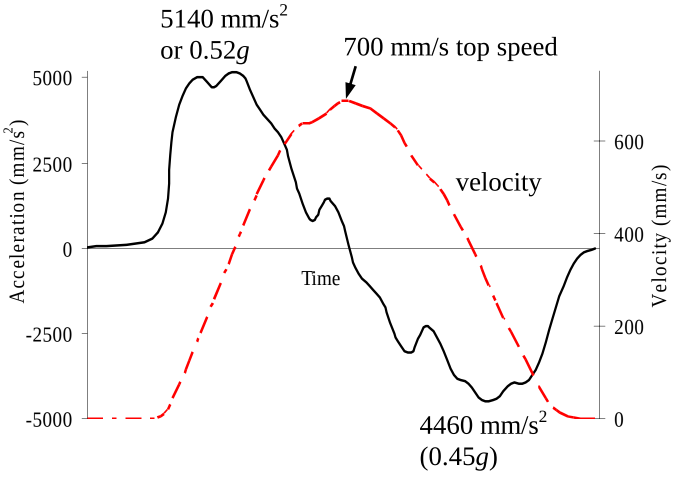
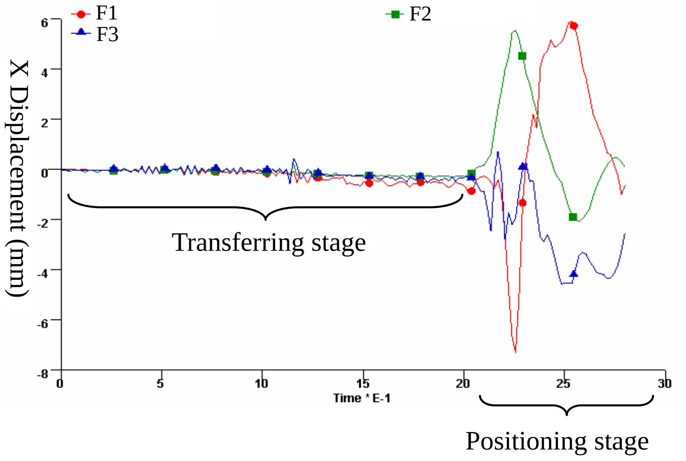
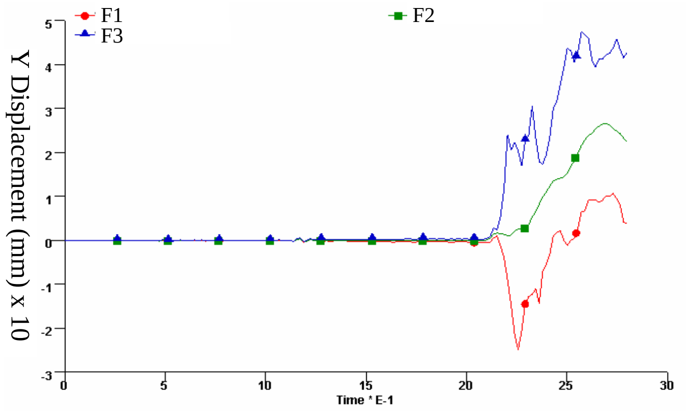


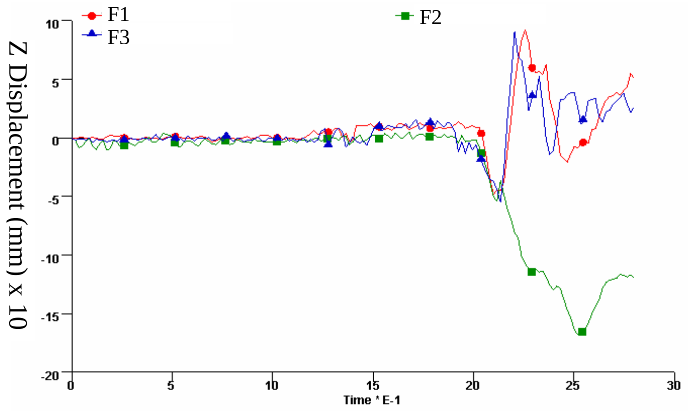
Fig. 4. Plots of velocity and acceleration in lifting operation



Front check points X displacement

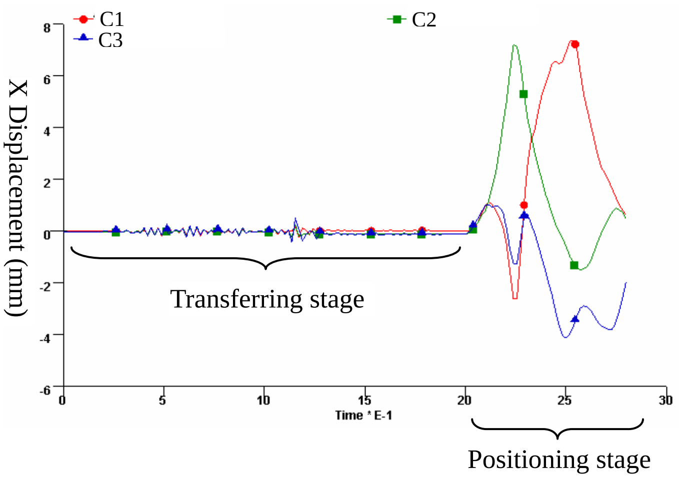


Front check points Y displacement

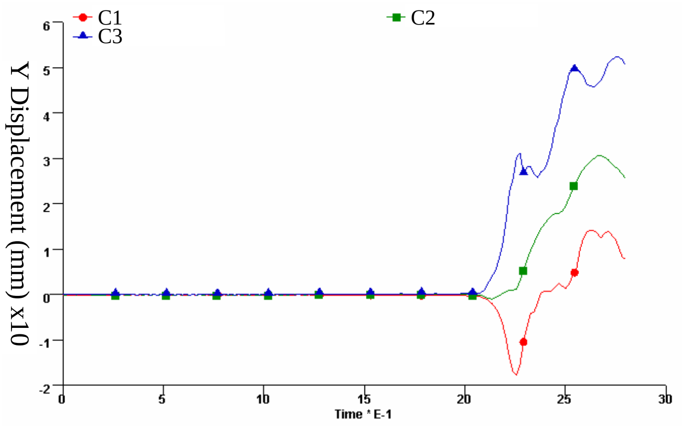


Front check points Z displacement

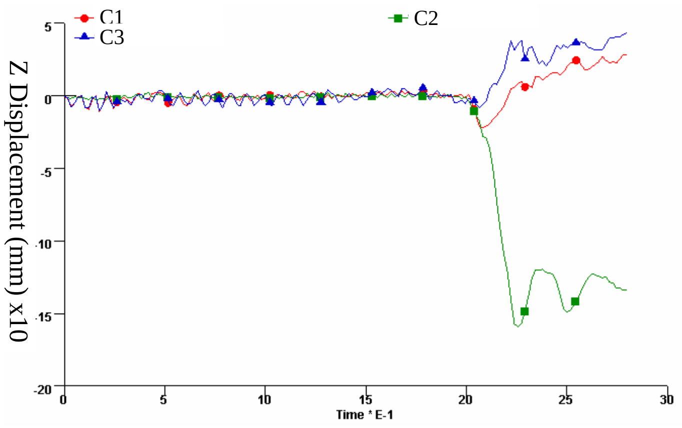
Fig. 5: Displacements of front edge check points



Central check points X displacement

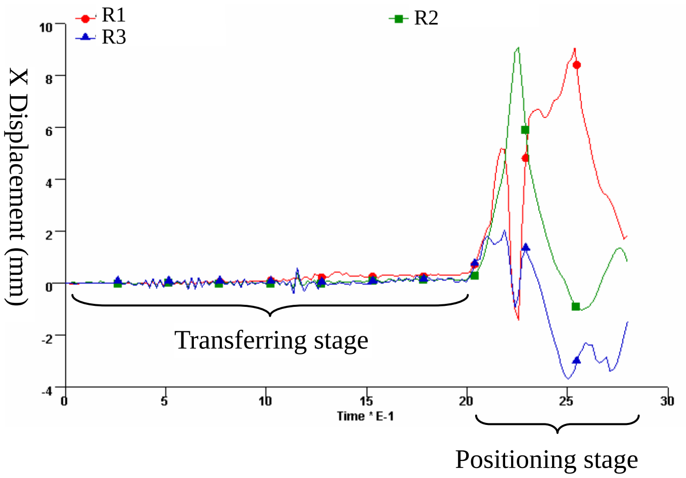


Central check points Y displacement

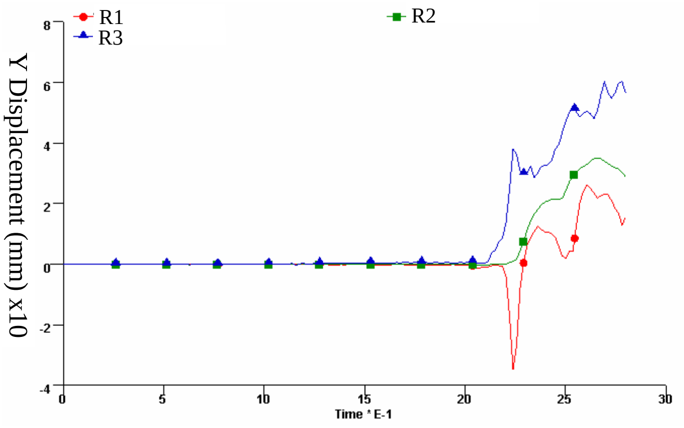


Central check points Z displacement

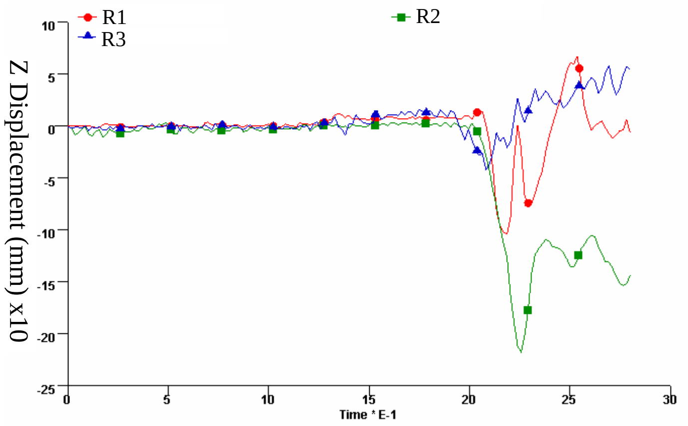
Fig. 6: Displacements of central area check points



Rear check points X displacement



Rear check points Y displacement

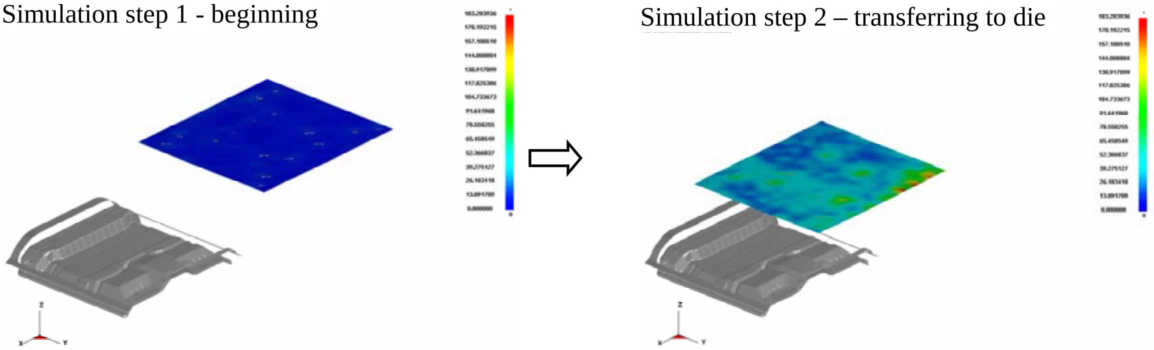


Rear check points Z displacement

Fig. 7: Displacements of rear check points

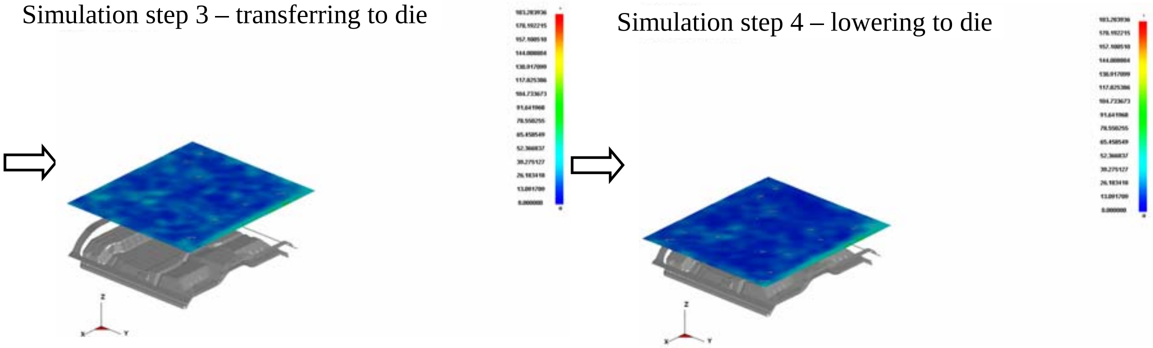
Simulation step 1 - beginning

Simulation step 2 – transferring to die



Simulation step 3 – transferring to die

Simulation step 4 – lowering to die



Simulation step 5 – releasing to die

Simulation step 6 – contacting with die

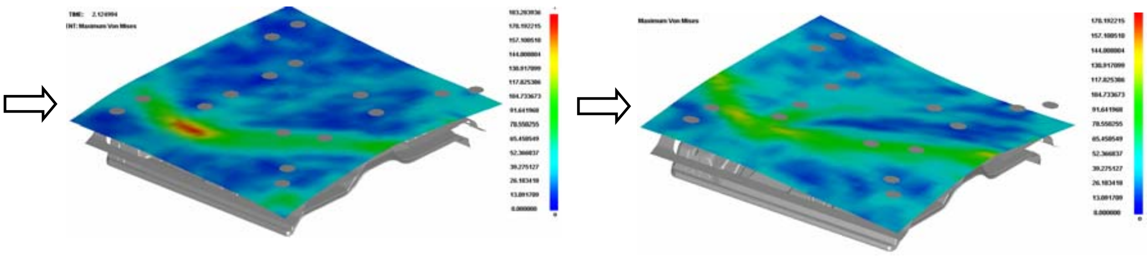


Fig. 8: von-Mises stress distribution on the deformed sheet-metal

	Nodal point displacement (mm)			
	Nodal point	X	Y	Z
Front edge	F1	-0.4	3	42
	F2	0.5	22	-118
	F3	-2.3	41	19
Central area	C1	0.5	6	27
	C2	0.3	26	-135
	C3	-2.2	51	42
Rear edge	R1	1.7	12	-18
	R2	0.6	26	-164
	R3	-1.6	58	48

Tab. 1: Summary of final deformations

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