Modeling and Optimization of End Effector Layout for Handling Compliant Sheet Metal Parts

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Material handling of compliant parts is one of the most critical and underresearched problems in the sheet metal stamping industry. The fundamental shortcoming of currently studied material handling systems for sheet metal stamping is the lack of analysis of its impact on part dimensional quality and production throughput. This paper addresses this problem by development of a generic methodology for modeling and optimization of part holding end-effector layout in order to minimize part dimensional deformation during handling operations. The methodology extends the design of ''N-2-1'' fixturing layout by adding part movability conditions. It considers part CAD model, handling direction and motion kinematic parameters to determine the best end effector layout. This methodology is realized by integrating FEM part and loading modeling with the optimization algorithm. It can be implemented into the design stage of a stamping line so that the trial and error process, which is current industrial practice, can be greatly shortened and the production throughput increased. Experimental results verify the proposed part holding end-effector layout methodology. [DOI: 10.1115/1.1366682]

1 Introduction

1.1 Problem Statement. Manufacturing processes of compliant stamped sheet metal parts are broadly used in such various industries as automotive, aerospace, aircraft, appliance, furniture and others. For example, on average, an automotive body is comprised of 150 to 250 large sheet metal parts with different shapes and sizes, which are produced at stamping plants in mass quantities. Parts are manufactured by different stamping operations in different presses (station), and then must be moved (1) between stations within a press line (Fig. 1), (2) between production press lines, and (3) between manufacturing facilities (for example between stamping and assembly plants).

The handling of stamped parts was recently identified as one of the top five causes of part dimensional variation [1]. The compliance of stamped sheet metal parts can cause their deformation during the handling process, which further causes part dimensional variation and in effect limits the transfer speed. It has been observed that material in a stamping facility spends over ninety percent of its time waiting to be moved and processed [2]. Efforts to reduce the gap between the capability of presses (and assembly stations) and the equipment feeding them have not been sufficient because (a) there has been little research on how material handling affects dimensional variation of stamped parts [1–4], and (b) there has been no available methodology for optimally designing these systems. Currently, the practice of setting up and running material handling equipment in a stamping plant is based on ''tryout''—a trial and error method. Systematic design rules are not available for the control of part quality and its impact on production rate.

Previous studies revealed that part holding end effector locations have a significant impact on the part dimensional quality [1,3]. Therefore, to increase the product throughput and to maintain good part quality, it is very important to identify the optimal part holding end effector layout during part handling.

This paper addresses this problem by developing a generic methodology for optimization of the part holding end effector layout in order to minimize part dimensional deformation during handling operations. The developed methodology focuses on dynamic analysis of the compliant sheet metal part deformation behavior. Motion acceleration-caused inertia force is considered. It is based on a part holding FEA model, a nonlinear optimization model, and an automatic procedure for integrating the FEA and the optimization models.

In Section 2, this paper presents the overall methodology for the dynamic end effector design. Section 3 presents the development of the part holding model—*rigid point contact model*. Section 4 describes the end effector layout optimization model and the MPC (multi point constraint) feature used for solving the FEA remeshing problem. Section 5 presents the experimental verification of the developed methodology, including experimental setup, measurement principle, and experimental results. Section 6 summarizes and gives conclusions.

1.2 Literature Review. While extensive research has been done on the material handling issue, most efforts investigated workshop or facility layout [5], materials flow routing [6], scheduling [7], or integrated control [8]. The main purpose of these research efforts has been to increase the throughput of the whole production system. Part quality due to handling operations has not been taken into consideration. In addition, the handled parts are considered to be rigid, having no influence on the material handling system.

In reality, many material handling processes deal with nonrigid products and parts. The automated handling of these nonrigid parts is a greater challenge, as the parts may deform significantly under handling forces. Little research has been done in the material handling processes that deal with nonrigid products [9]. Some initial studies were conducted in the garment industry [10], the aerospace industry [11], and the handling of visco-elastic/plastic dough cords [12]. In these studies, the nonrigidity of the handled parts are very different from sheet metal parts.

The problem of part holding end effector layout is similar to fixture design, since end effectors perform locating and clamping functions. Recently, fixture modeling and design have been thoroughly studied and significant results have been achieved [13]. The research in fixture design can be categorized into two groups: research for rigid parts and for compliant sheet metal parts. Regarding rigid parts, kinematic and mechanical methods such as screw theory [14,15] and force equilibrium equations [16] are most often used for functional configuration of fixture. Menassa

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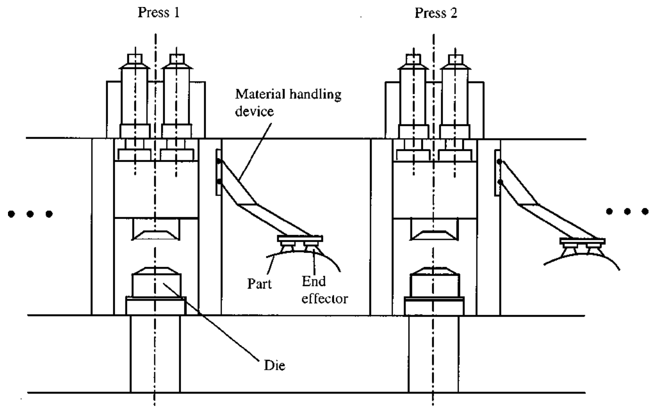


Fig. 1 An example of a material handling system in a stamping line

Table 1 Classification of fixture research based on static/movable conditions

	Static fixtures	*Movable fixtures*
Rigid parts	• 3-2-1 fixture design methodologies - kinematic analysis - screw theory (Asada & By, 1985; Chou et al. 1989) - force equilibrium equation (Salisbury and Roth, 1983) - fixture layout optimization (Menassa & DeVries, 1989; Hockenberger & DeMeter, 1995) - Accessibility analysis (Wu et al., 1998)	• "Peg & hole" fixturing problem
Compliant parts	• N-2-1 fixture design methodology (Youcef-Toumi, et al., 1988; Cai et al. 1996; DeMeter, 1998)	• "Peg & hole" fixturing problem (1-D studies) - Motion control - Path planning

and DeVries [17,18] developed an optimal fixture design technique that can minimize part deflection normal to the primary reference plane. The design variables are three fixture locators on primary datum as required by the ''3-2-1'' principle. DeMeter [19] presented a min-max algorithm to determine the optimal fixture layout and clamping force intensity that minimizes the maximum contact force. Wu et al. [20] presented an analysis on fixturing accuracy, clamp planning, fixturing accessibility, and clamping stability.

In the research for compliant sheet metal parts, Youcef-Toumi et al. [21] proposed a method for *sheet metal fixturing analysis*. They studied three- and four-point fixturing systems for flat plates and shells to arrange the fixture so that the stress in the part is below the material yield stress. Cai et al. [22] proposed a technique of *optimal sheet metal fixturing design*. The objective is to minimize part deflection rather than stress and strain. They formulated the ''N-2-1'' fixture layout principle for constraining compliant sheet metal parts. DeMeter [23] presents a fast support layout optimization (FSLO) model to minimize the maximum displacement-to-tolerance ratio of a set of workpiece features subject to a system of machining loads. The speed-up of the optimization is obtained by a reduced stiffness matrix approach. First, the model stiffness matrix is extracted. Then, the matrix is reduced by manipulation based on the selected degrees of freedom. Li and Melkote [24] present an elastic contact model to reduce workpiece locating error due to rigid body displacement through fixture layout optimization.

Regarding the fixture element (end effector) modeling, most of the literature assumes point contact and frictionless locating. Nguyen [25] grouped the locators as frictionless point contact, hard-finger contact and soft-finger contact in his research of constructing force-closure grasps based on the shape of the grasped object. DeMeter [26] expanded the fixture design realm by considering the planar, spherical and cylindrical surface contacts between the workpiece and fixture elements.

All previous research related to fixture modeling and design considers parts in static conditions. The research is analyzed in terms of its ability to satisfy the following four functional requirements for holding workpieces: (1) locating stability, (2) deterministic workpiece location, (3) clamping stability, and (4) total restraint [15]. However, for material handling operations, the part-fixture system is moving. The part-fixture *movability conditions* are essential and have not yet been addressed in fixturing research literature. Table 1 positions material handling end effector design methodology among current fixturing research.

The movability restraint can be stated as:

When a part is constrained in an end-effector during handling operations, it should (a) withstand every possible dynamic forces resultant from motion, and (b) minimize part distortion (plastic and elastic) caused by motion.

This condition has unique features, which are directly related to the physical conditions of the material handling: (i) the part cannot be dropped, i.e., needs to withstand every possible dynamic force; (ii) the part cannot be permanently distorted (plastic deformation decreases part dimensional quality); and (iii) part elastic deformation needs to be minimized (decrease of part deformation during handling reduces part nesting error in die; it also reduces potential interferences between part and production equipment, allowing for a higher production rate).

From another point of view, the part holding mechanism can be analyzed in terms of form closure and force closure. A holding is form closure if the part is totally constrained by the set of contacts, irrespective of the magnitude of the contact forces. A force closure fixture makes use of forces to capture the main constraint between the fixture and the part [25]. The forces used are typically friction force as in a suction cup, or the grippers on a robot arm.

Previous research of force closure focused on static equilibrium, and in most cases the parts under research were considered to be rigid [25,26]. In this paper, the part holding mechanism is a force closure. However, our research focuses on the dynamic behavior of the compliant sheet metal parts. The acceleration-caused inertia force is considered.

In summary, the main characteristics of material handling for sheet metal parts are listed as follows:

(1) The direction of the holding force changes during the handling process. This is because parts need to be handled along a given trajectory, as shown in Fig. 2. This is different from fixture design, where the primary force is almost perpendicular to the primary datum plane. Figure 3 shows an example of N-2-1 layout in fixture design, in which the angle ϕ is assumed to be small. In N-2-1 layout, it is assumed that the part is rigid in the secondary and tertiary datum planes and is compliant only in the primary datum plane.

(2) The rigidity in the secondary and tertiary plane depends on the constraints in the primary datum plane. For example, in Fig. 4(a), the constraint in the primary datum plane is sufficient for

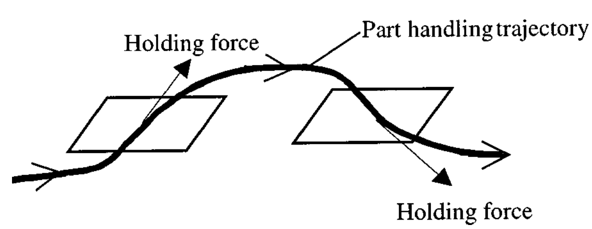


Fig. 2 An example of a part handling trajectory

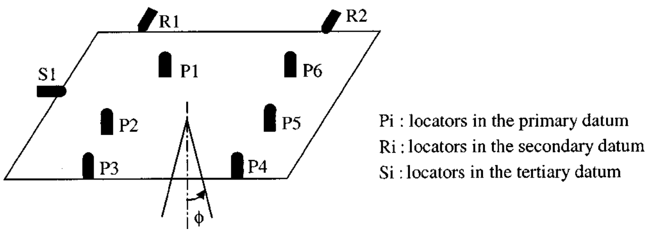


Fig. 3 An example of N-2-1 layout

acting forces, thus, the part behaves as a rigid one in the secondary and the tertiary datum planes. In the case shown in Fig. 4(b), the constraint end effector layout in the primary datum plane is not sufficient for acting forces, thus the part does not behave in the secondary and tertiary plane as rigid, causing the buckling of the part.

(3) Loading is inertia force and air resistance, which are dynamically applied to the whole part. This is also different from fixture design, where the part loading is the machining force (gravity is neglected). The machining force is a dynamic loading only applied to the point of the part being machined.

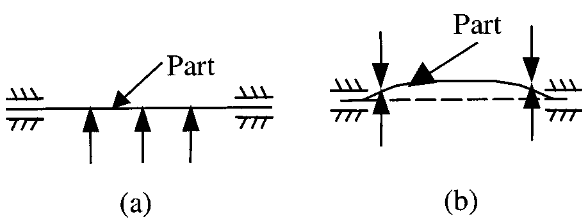


Fig. 4 Impact of the locating layout in the primary datum plane on the rigidity in the other two planes

(4) The fixturing rule for the end effector design should satisfy *movability restraint*. The end effector layout should constrain all of a part's DOFs under the dynamic conditions: *End-effector Layout*=**Function** *(number of DOFs for given part motion dynamic conditions)*

2 Methodology for End Efector Layout

From the previous discussion, it can be seen that in compliant part holding end effector design, the loading is dynamically applied to the whole part. The part deformation will change with motion velocity and acceleration. Due to these characteristics, the currently existing approaches in fixture design are not directly applicable for modeling and designing end effectors for handling sheet metal parts. In order to solve the problem of dynamic end effector layout design, a part holding model needs to be developed to analyze the part deformation behavior during the material handling process. Then an optimization scheme should be incorporated with the part holding model.

The procedure of dynamic end effector layout design is shown in Fig. 5 and summarized as the following steps:

Step 1: The part geometry (CAD information) is input and meshed.

Step 2: Loadings of the gravity and the acceleration force are applied and an initial end effector layout is defined by applying proper displacement constraints on the points to be defined as end effector locations.

Step 3: Finite element calculation is conducted and the part deformation is obtained as an output.

Step 4: If the deformation exceeds the elastic limit at some points, this end effector layout is not acceptable. A new layout is generated and the elastic limit is checked again till the elastic limit is not exceeded. If no feasible points are found, this means that under the given acceleration no end effector layout exists to hold the part so that yield can be avoided. At this point, the handling

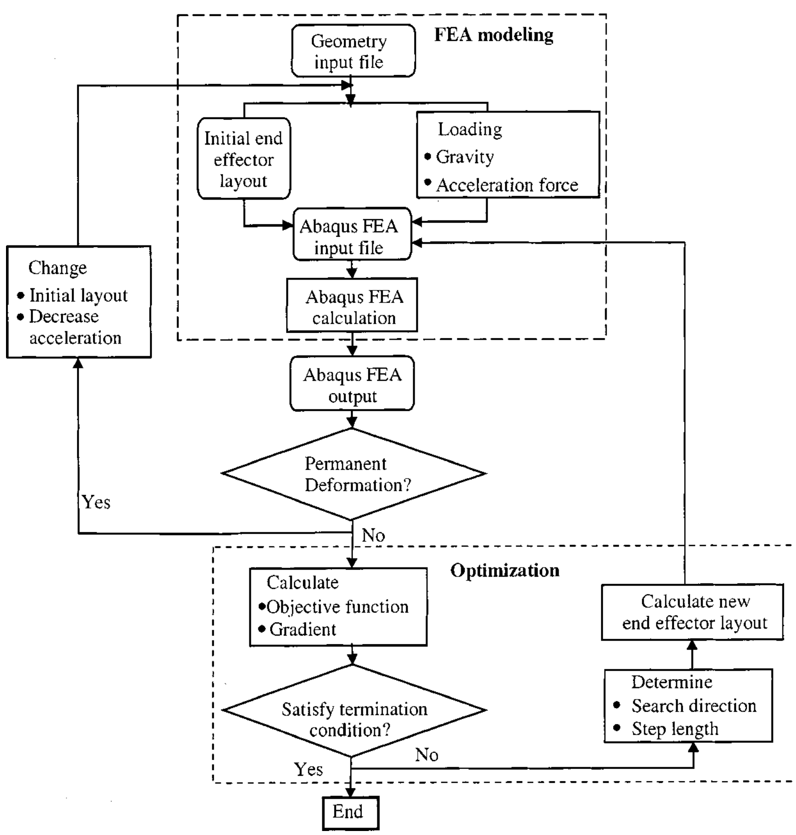


Fig. 5 The end effector layout design procedure

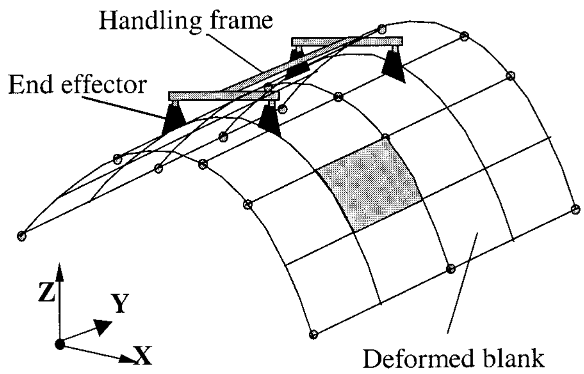


Fig. 6 Part holding model

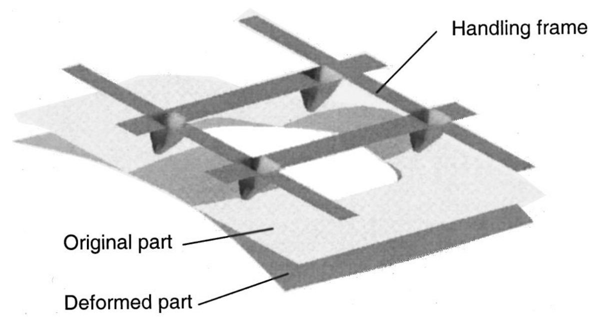


Fig. 7 Part deformation simulation

acceleration must be changed. Then, another iteration is performed. If the part deformation is within the elastic limit, the objective function of the optimization and its gradient are calculated. Based on the information from the objective function gradient, the search direction and the step size are determined, and a new iteration is performed. In practice, for most parts the applicable acceleration (less than 20 m/s^2) will not cause plastic deformation. Therefore, in the following presentation of the presented methodology, we will only consider elastic deformation.

Step 5: The search and calculation cycle is continued until the termination conditions are satisfied. The end effector layout under the termination conditions is the optimal layout.

In most cases, the handling of blanks is the bottleneck stage for the production cycle time. This is because blanks have relatively large flexibility and thus large deformation compared with other intermediate stages of the stamped part. The stamping usually makes the sheet metal stiffer, reducing its deformation. Therefore, our investigation focuses on the material handling issue for sheet metal blanks. However, the methodology can be applied to other stamped parts with already preformed shape as well.

A detailed description of the part holding modeling and the optimization scheme for the end effector layout is presented in Sections 3 and 4, respectively.

3 Part Holding Modeling

Since stamped parts can be described as arbitrary three-dimensional geometry, an FEA model is used to simulate the part deformation behavior and give quantitative predictions. The part deformation during handling is schematically shown in Fig. 6.

The finite element analysis software HYPERMESH is used to generate the part geometry mesh. ABAQUS is used for applying loading and displacement boundary conditions, as well as for conducting the calculation. The sheet metal parts are modeled as shell or plate elements. We used 4-noded S4R5 shell elements in our study. A rigid point contact model is developed for the part holding end effector. By rigid point contact model, we mean that the part holding end effector is modeled as a point rigidly fixed to the handled part. Its geometric shape and material properties are not considered. The part transfer acceleration and the part gravity can be applied to the part by specifying them in the FEA input file. As will be presented in Section 4, it is the deviation of the part deformation from a given die contour that impacts the part quality. Since the acceleration in the vertical direction has bigger influence on the part deformation than acceleration in the horizontal direction, we focus on the acceleration in the vertical direction in our FEA simulation.

Figure 7 shows an example of simulation result using the developed model. The part is a side frame from a 2-door truck. The acceleration used in this simulation is a constant upwards. In this simulation, four end effectors are used.

In this paper, we do not research on how to select the number of end effectors used in the modeling and optimization. In the case study of handling the fender blank, which will be presented in Section 5, four end effectors were chosen following the current state-of-the-art industrial setup. By selecting the same number of end effectors, we are able to evaluate the validity of our methodology compared with the current state-of-the-art industrial practice.

4 End Effector Layout Optimization

Once the finite element model has been formulated, deflections can be calculated. The deflections of certain significant nodes can be used to evaluate the objective function for the end effector layout optimization. The end effector layout optimization is a constrained nonlinear optimization problem. The optimization model can be explained using Fig. 8, in which a blank part is handled. In Fig. 8(a), $P_i(i=1,\ldots,n)$ denotes the critical points whose deformations will be used to represent the overall deformation of the part. $H_i(i=1,\ldots,4)$ represents the end effector locations. The number of end effectors depends on the part geometry, material property and user-defined criteria. We use four end effectors as an example. The length and width of the part are a and b respectively. δ and γ represent the overlap distances used for the search range during optimization. In Fig. 8(b), $P_i'(i=1,\ldots,n)$ denotes

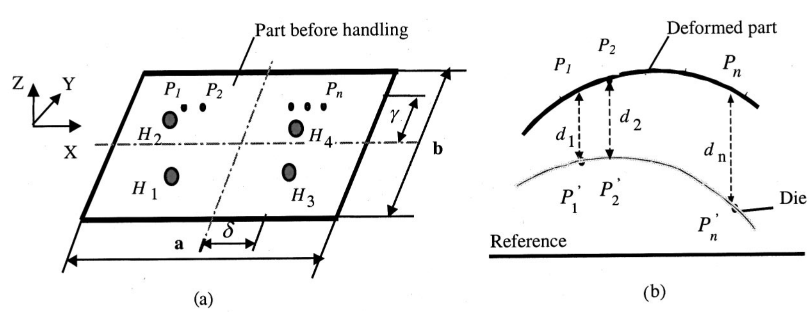


Fig. 8 Principle of optimization scheme

the points on the die which correspond to the critical points on the part, and $d_i(i=1,\ldots,n)$ denotes the deviation of the deformed part shape from the die contour.

The optimization model is presented as follows:

(i) Design variables: The end effector locations $H_i(x,y,z)$ $(i=1,\ldots,4)$

(ii) Objective function:

Based on the current studies, two kinds of objective functions were of importance:

(a) Minimization of part deflection from a given die contour. This function is used for handling sheet metal blanks before the first stamping operation (drawing operation). This objective function eliminates ''leaf dropping'' situations and reduces part nesting errors in a stamping die.

(b) Minimization of part deflection from the part static position. It is used for intermediate stages of stamping process, when the part shape is partially determined. For example, after drawing operations, during trimming, piercing or flanging operations. This objective function minimizes part deflection caused by handling operations (part motion).

Since our research focuses on the material handling for the sheet metal blank, this paper will investigate the first type of objective function, as illustrated in Fig. 8. The objective function minimizes the standard deviation of the deformed part shape (represented by selected critical points) from the die contour. i.e.,

$$\min F(H)=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(d_i-\overline{d})^2} \tag{1}$$

where,

$$\overline{d}=\frac{1}{n}\sum_{i=1}^{n}d_i \tag{2}$$

The mean deviation $\overline{d}$ is zero when the part is directly transferred onto the die. However, in current industrial practice, sheet metal parts are usually released from the handling system at some distance above the die. Thus, the mean deviation is not zero. In these situations, it can be seen from the following that the influence of the mean deviation can be minimized by controlling the part free-falling distance.

The whole material handling process can be divided into two stages: (1) the part transfer stage when the part is held by end effectors; and (2) the part free-falling stage after the part is released. Because of these two stages, the final deformation shape of the sheet metal part at the moment the part hits the die is determined by two factors: (1) the deformation shape at the moment the part is released from the end effector; and (2) the deformation change due to the free-falling process. The deformation shape at the moment the part is released is affected by the end effector layout, which is addressed in this paper. The deformation change due to the free-falling process is determined by the falling distance, the wind resistance, and the part geometry and material-related vibration frequencies. Preliminary study indicates that by calculating the fundamental frequency of the part in the free-falling process, it is possible to obtain the desired part deformation shape by coordinating the initial part deformation shape at the moment it begins to fall and its free-falling distance [4]. Therefore, the optimization objective function can be defined as the sum squares of the deviations, and the larger mean deviation can be left as a control variable.

(iii) Constraints:

Constraints are to limit the search area for the end effector location positions. If the origin of the coordinate system is set at the center of the part, then the constraints are:

$$\begin{aligned}-a/2\leqslant H_{1x}=H_{2x}\leqslant\delta\\ -\delta\leqslant H_{3x}=H_{4x}\leqslant a/2\\ -b/2\leqslant H_{1y}=H_{3y}\leqslant\gamma\\ -\gamma\leqslant H_{2y}=H_{4y}\leqslant b/2\end{aligned} \tag{3}$$

(iv) Gradient:

The gradient of the objective function is determined by using the finite difference method, because the analytical relationship between the function F(H) and the end effector layout H cannot be found for parts with arbitrary geometry and holding positions. At each end effector location, the FEA program is called and the objective function is generated. Then a small perturbation is given independently and the objective functions corresponding to the perturbations are generated. After that, the objective function gradient vector, **g**, is approximated.

$$\mathbf{g}=[g_1,\ldots,g_i,\ldots,g_m]^T \tag{4}$$

where

$$g_i=\frac{F(H+\Delta H_i)-F(H)}{\|\Delta H_i\|} \tag{5}$$

$$\Delta H_i=[0,\ldots,\varepsilon_i,\ldots,0]^T \quad i=1,\ldots,\mathrm{m} \tag{6}$$

where ε_i is the perturbation in the ith searching direction, and m=(Number of end effectors)* (Number of search directions)

End effector constraints as defined in Eq. (3) serve as the boundary conditions for the FEA model. When an end effector is located at a finite element node, it can be modeled as a constraint associated with the node. However, when an end effector is located at an arbitrary position, more effort needs to be done before boundary conditions can be defined. This is because the standard finite element model usually requires the boundary conditions to be defined at finite element nodes only. Two methods can be used to solve this problem: remeshing to assure the fixture end effector locations are always at finite element nodes [18] or using the Multi-Point-Constraint (MPC) feature. As stated by Rearick et al. [27], the remeshing algorithm may be not reliable in some circumstances.

In this paper, the MPC feature was used. In ABAQUS, this feature is realized by using a specially formatted ''Equation'' command. For 2D problem and four-noded elements as in our case, the Equation command can be formulated as:

$$\sum_{i=1}^{4}c_iw_i=0 \tag{7}$$

where c_i are coefficients, and w_i are degree of freedoms. Thus, the position of a modeled end effector can be approximated based on the coordinates of four adjacent finite element nodes.

A sequential quadratic programming technique implemented as in the VMCON subroutine is used for the optimization of end effector layout. VMCON uses an algorithm proposed and first implemented by M. J. D. Powell. Powell's algorithm solves a sequence of positive definite quadratic programming subproblems. Each solution determines a direction in which a one-dimensional minimization is performed. An interface between the FEA and VMCON modules is developed, so that the whole process can run automatically. From the number of end effectors and their initial positions, boundary, and loading conditions, ABAQUS will perform a finite element analysis to calculate the deflections of the sheet metal part. From the deflection information, the objective function and the objective function gradients for VMCON optimization are obtained. At each iteration, the termination conditions defined by the user are checked to see if an optimal solution is reached. If not, the end effector locations are updated according to the objective function and its gradient information. At this stage, the positions of the end effectors are iden-

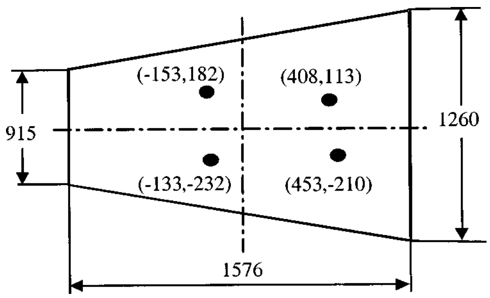


Fig. 9 Dimensions and the initial end effector layout for the fender blank

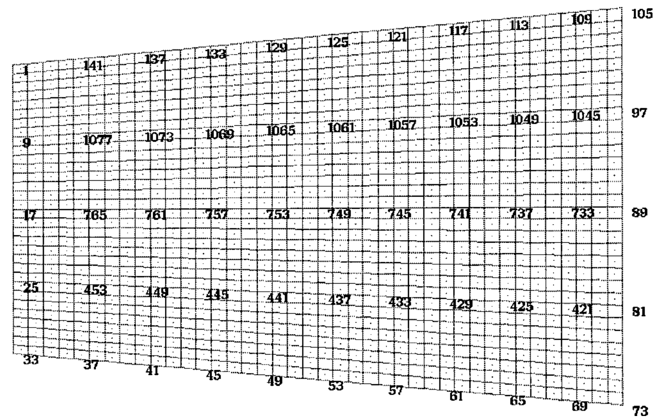


Fig. 10 FEA mesh and the critical points for the fender blank

tified as finite element local coordinates, and the Equation functions are formulated [Eq. (7)]. Finally, the ABAQUS input data file is updated to start a new optimization iteration.

5 Simulation and Experimental Verification

The objective of experimental verification is twofold:

1 Verification of modeling and optimization procedure

2 Determination of significance of the developed methodology by comparing the result from end-effector layout currently used in industry with the result from the layout optimized using the developed methodology

The experimental verification was conducted in five steps:

(i) modeling a few industrial cases: selected parts with currently used state-of-the-art industrial end effector layout;

(ii) modeling and identification of optimum end effector layout for a selected industrial case using developed methodology;

(iii) conducting experiments in conditions described in items (i) and (ii) (see later part of this section for description of experimental setup);

(iv) analysis of error between simulations (items i and ii) and experiments (item iii)

(v) comparison of improvement between items (i) and (ii): industrial and optimized end effector layout

Experiments were conducted (a) for different stamped parts: fender, door inner, side frame; (b) in different directions of handling motion: horizontal, vertical, and generic linear direction; (c) with different speed and acceleration. It turned out that the part deformation is highly dependent on the vertical motion parameters. Due to space limitations, this paper presents only the result of handling a fender blank in the vertical direction under a 0.62 g acceleration. The objective function in this test is to minimize the part deformation relative to a horizontal reference plane.

The dimensions of this steel fender blank are: length 1576 mm, smaller side width 915 mm larger side width 1260mm, and thickness 0.9 mm. The elastic modulus $E=2.07\times10^5$ MPa and Poisson's ratio $\nu=0.3$. The dimensions and the initial end effector layout are shown in Fig. 9. The FEA meshes are 40 in length direction and 32 in width direction, as shown in Fig. 10. Points 1, 141, 137, 133, 129, 125, 121, 117, 113, 109 and 105 serve as the checking points during the experiment (Fig. 10). The deflections of these points will be compared between the FEA prediction and the test results. The selection of checking points is based on two criteria: (1) critical characteristics determined during design process (Key Control Characteristics-KCC and Key Product Characteristics-KPC) [28], and (2) points with estimated large deflections during the handling operations.

The verification test was conducted on an overhead gantry with controllable x and z-axes using a specially designed flexible end effector fixture (Fig. 11). The rotary sensors were used for measuring part deflection. The part deflection is calculated by the angular change of the rotary device. The details of the measurement principle are shown in Fig. 12. In Fig. 12, d is the offset of the linkage, which can be adjusted according to the experiment requirement. The variable 1 represents the length of the whisker. α indicates the initial angle of the measurement point relative to the reference horizontal plane, β indicates the final angle after the deformation of the part, and θ is the real angular change before and after the deformation of the part, which can be measured by the rotary sensor directly. R stands for the rotation radius of the whisker tip. H represents the position of the measurement point from the reference horizontal plane, and X is the position of the measurement point from its initial position in the horizontal length direction. The required variables can be calculated from the equations shown in Fig. 12.

The deformation of a measurement point in vertical direction is calculated as $(H-d)$.

The test and FEA simulation results are shown in Fig. 13. Figure 13(a) shows the end effector layout change from the original position ABCD (used in industry) to the calculated optimal position A′B′C′D′ Figure 13(b) shows the test results with the two layouts and the FEA simulation result at the optimal cup layout. It can be concluded from Fig. 13 that:

1 The FEA simulation of stamped part deformation is accurate for material handling application. The average error of the FEA prediction curve relative to the test curve for the eight measured points is less than 5 percent. The largest difference was observed

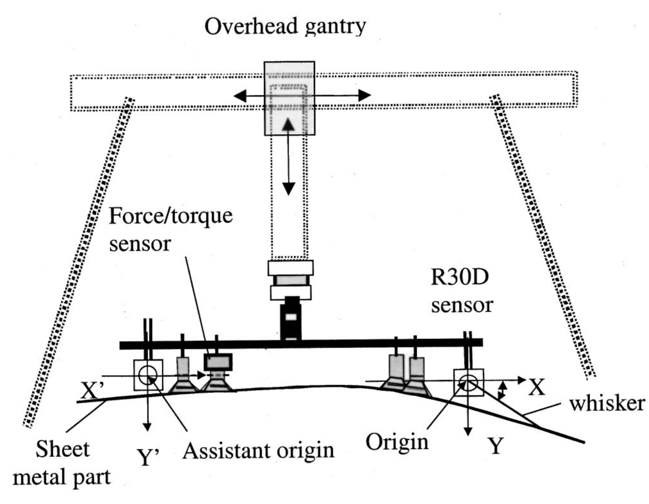


Fig. 11 The measurement setup

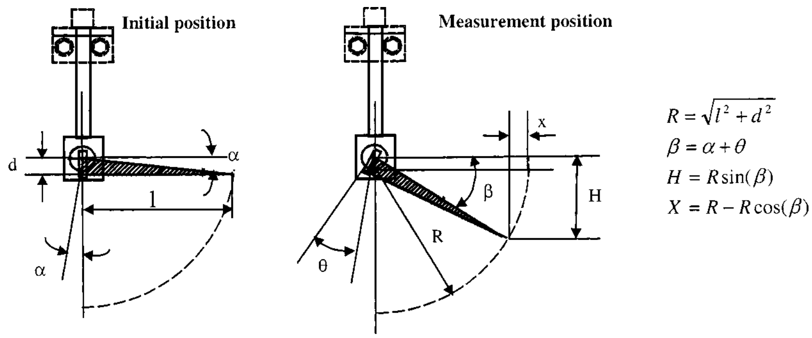


Fig. 12 The measurement principle

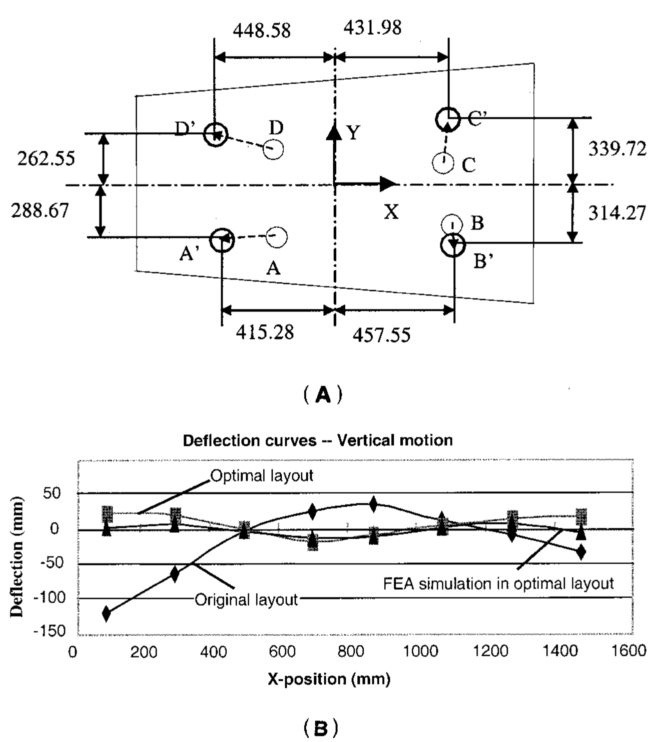
at points located close to the part edge (boundary points on both ends) due to the cup model torsional stiffness difference.

2 The optimization method incorporated with the FEA modeling is effective. The maximum part deflection range is reduced significantly with the optimal end effector layout. The maximum part deflection for the original layout, which is currently used in industrial practice, is 156.6 mm: the maximum deflection for the optimal layout is 42.7 mm. This means that given the same part deflection tolerance, with optimal end effector layout, the part can be handled with higher speed (increasing production rate). Rough calculation suggests that the increase of the production rate could reach above 10 percent in the case of fender blank production. This means that for a stamping line with press rate at 15 strokes per minute, which is quite usual in a stamping plant, for a standard eight-hour shift, 720 more parts can be produced.

6 Summary and Conclusion

Compliant sheet metal parts are widely used in various manufacturing processes including automotive, aerospace, appliance and furniture industries. Recently material handling of compliant sheet metal parts has been identified as one of the most critical problems (one of the top five causes of part dimensional variation for large automotive parts), and yet is an underresearched area in stamping industry. The major shortcoming of research on material handling is the lack of analysis of its impact on part dimensional quality, and impact of part quality on production rate.

This paper develops a generic methodology for modeling and optimization of part holding end effector layout to minimize part dimensional deformation during handling operations. The developed methodology extends the ''N-2-1'' fixture layout design methodology by introducing a movability restraint condition which is essential for material handling fixture design, but has not yet been addressed in the current fixture design research literature. The presented methodology focuses on dynamic analysis of compliant sheet metal parts. Motion acceleration-caused inertia force is considered. The methodology is based on the CAD part model, handling kinematic and dynamic parameters model, end effector model, and the nonlinear optimization module. The methodology links FEM model with optimization module so that the whole optimization iteration can be run automatically without human intervention. The remeshing problem between iterations was eliminated by using the multi-point constraint (MPC) feature of the FEM package. The validity of the proposed methodology is verified through a series of experimental tests and the comparison of the test results with the simulation results as well as with real industrial practice results.



(A)

(B)

Fig. 13 Results of the FEA optimization and the test for the fender blank (*a*) The original and the optimal cup layout (*b*) Part deflection

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