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Sheet-Stamping Process Simulation and Optimization

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This paper presents the development and implementation of a generalized optimization framework for use in sheet-stamping process simulation by finite element analysis. The generic computational framework consists of three main elements: a process simulation program, an optimization code, and a response filtering program which are linked together using a script program. These elements can be filled by any combination of applicable software. Example sheet-stamping process simulations are presented to demonstrate the versatility of the framework for use in various forming scenarios. Examples presented include a 2-dimensional single-stage forming, a 2-dimensional multi-stage forming, and a 3-dimensional single-stage forming process. A forming limit diagram is used to define failure in the 3-dimensional process simulation. Optimization results are presented using press speed minimization and failure rate minimization with aluminum 6061-T6 blanks.

I. Introduction

The complexity of sheet-stamping stems from the large plastic deformations required in production. The process is influenced by die geometry, die holding force, interface friction, part and die temperatures, forming speed, and other factors. Poor selection of these parameters can negatively affect the quality of the workpiece resulting in damage due to wrinkling, tearing, excessive spring back, and thinning.

With mass production becoming more prevalent, increasing demands are being placed on finding sheet-stamping process designs that are more cost efficient, less wasteful of material, faster, and result in a higher quality part. Traditionally sheet-stamping design is performed purely on a trial and error basis with success largely dependent on the experience of the manufacturing engineers and technicians. This approach is far from optimum and could become costly and time consuming when the number of design iterations grows. Each forming stage in the sheet-stamping process adds to the complexity of the problem by introducing more design parameters thus increasing the difficulty of finding the best solution.

The rise of finite element analysis (FEA) tools capable of performing sheet-stamping simulations has inevitably piqued the interest of process designers and has positioned process design to take a more automated approach. The inclusion of FE simulation in design provides a quicker and less expensive alternative to physical testing of different design concepts. The addition of optimization to this pairing advances the proficiency of a design engineer even further by allowing design iterations to be implemented autonomously. Particularly applicable to sheet-stamping is the advancement of FEA codes that can accurately capture the inelastic flow associated with large changes in sheet geometry.

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Research in the area of coupling FEA with optimization has been ongoing since the introduction of FEA. Researchers have used FE simulation codes to obtain better sheet stamping results[1-4]. Forming limit diagrams (FLD)[5-9] and other simulation responses[10-11] have been used in studies as a predictable way to determine material failure in sheet metal. Most of these studies focus mainly on either the optimization scheme or the process simulations themselves. Few studies are directed at the process optimization framework.

In this study, a generalized optimization framework is developed to organize and filter raw data from process simulation as well as facilitate the communication of all major elements in computational simulation and design. To demonstrate its implementation, the optimization framework is applied to simulations using example programs in place of the generic elements. The studied example problems aim to produce sheet-stamping aluminum 6061-T6 parts of high quality using different objectives and constraints to demonstrate the versatility of pairing optimization with FEA. Industry relevant optimization problems are optimized by increasing the forming speed and quality of the formed parts as indicated by a variety of responses including spring back, damage, residual stress, and FLD. Optimization results using the presented framework are also visualized in the form of three different problems: a 2-dimensional single-stage forming, a 2-dimensional multi-stage forming, and a 3-dimensional single-stage forming. A forming limit diagram is taken from literature to define failure in the 3-dimensional process simulation.

II. Process Simulation-Based Optimization Framework

The integration of design optimization and forming process simulation makes it possible to take advantage of advanced numerical search techniques to find an optimum set of process parameters for forming stamped part. Focus is on finding the best combination of process parameters that leads to an optimum product as measured in responses from the process simulation. This process is not a trivial task and involves the creation of communication programs and extensive research on the format of process simulation input and response formatting.

A. Generalized Process Simulation-Based Optimization Framework

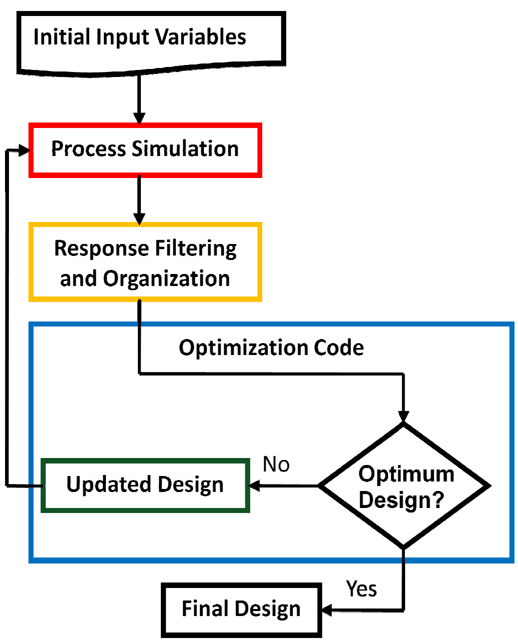


Figure 1. Generalized process simulation-based optimization framework.

The computational framework shown in Fig. 1 consists of three main tools: a process simulation program, an optimization code, and a response-filtering and organization program.

The setup of this framework involves creating a process simulation model with an initial set of process control parameters which can include any desired variables that represent the forming process. The process simulation model includes all the necessary components such as the workpiece, punch, die, and blank holders represented by separate geometric entities. The relative positions and contact definitions must be accurate for the forming simulation to work correctly due to the interaction of multiple components in a dynamic loading environment. This includes determination of the initial process parameters as well as die shapes and workpiece shape. The initial design parameters are fed into the process simulation FEA code which creates an output containing the process responses.

The raw data out of the process simulation must be filtered and organized to obtain relevant information for the optimization code. This can be done with a scripting program that is capable of sorting the relevant data out of the process simulation response files and creating a new file with enough data for the optimization code to develop an updated design point.

The optimization code then determines if the current set of design parameters satisfies the optimality criterion. If it is determined to be an optimum the cycle stops, but if the parameter set is determined to not be an optimum an updated design is created and used as input for another process simulation. This cycle continues until an optimum parameter set is obtained.

This generalized framework is independent of the specific tools used and can thus be applied with any number of combinations of software packages. The exact flow of information in the framework may vary depending on the tools selected by the designer.

B. Coupling Simulation and Optimization

To demonstrate the implementation of the previously discussed optimization framework, an example process simulation-based optimization scheme is presented. Figure 2 shows the flow diagram with specific tools selected for each element. This is merely one example of an optimization scheme that could be created with the presented framework. This specific example makes use of Simufact.forming[12]. as the process simulation software, a MATLAB[13] code as the response filtering and organization element, and VisualDOC[14] paired with VisualScript[15] as the optimization code. Simufact.forming was selected in this study for process simulation because of its affinity for forming mechanical parts. The coupling of these packages allows for sheet-stamping process simulation and optimization.

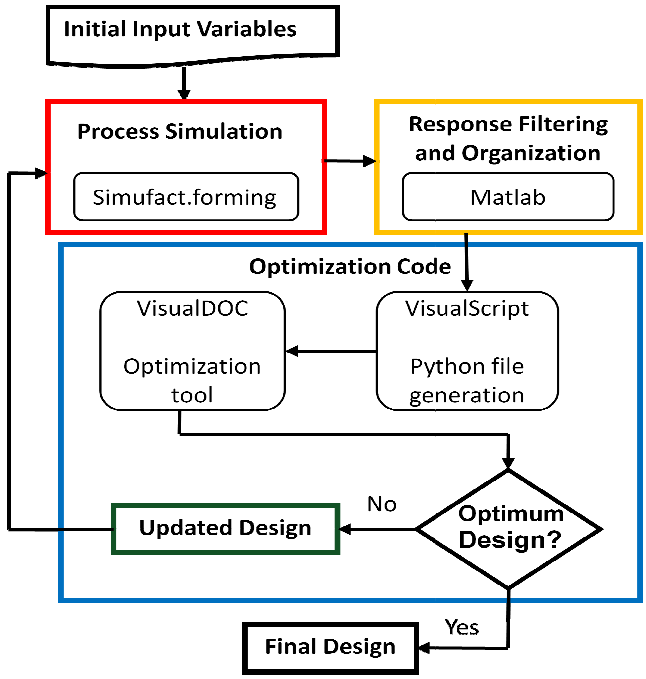


Figure 2. Example process simulation-based optimization framework.

The The optimization process begins by the user creating a baseline simulation model of the part in Simufact.forming. The simulation must be defined by a set of die and workpiece models and process parameters. This software allows for the use of die temperature, workpiece temperature, friction coefficient, press speed, and ambient temperature as process parameters. Once the initial process is created, the forming simulation is performed. The results from this simulation are merely used as baseline values.

MATLAB is utilized to filter and organize the responses from the process simulation output. The MATLAB program extracts the fields of relevant data from the response file and calculates average and maximum responses and compares the data with a prescribed FLD. These values are incorporated into constraints during optimization setup.

VisualScript is used as a feeder program for VisualDOC. It creates a python file with the locations of the MATLAB extracted values and process simulation input values. VisualDOC uses this file to locate and alter the input for Simufact.forming and compare results at design iterations.

C. Response Filtering and Organization

Effective stress, effective plastic strain, major strain, minor strain, grain size, and damage are output directly for each element integration point from Simufact.forming. Spring back, thinning, and FLD failure are not directly output and must be calculated from other output responses. After the MATLAB program has extracted the relevant data, it calculates response values for use in optimization.

1. Spring back and thinning

Spring back values are not directly output from the forming simulation. These values must be calculated from the direct output data of element integration point displacement and element thickness. Spring back values are calculated by taking the difference of the displacements before and after the forming tools are removed from the workpiece as shown in Eq. (1). The thinning values are calculated by taking the difference of the final element thickness and the initial element thickness as shown in Eq. (2).

(1)

$$T = th(t_0) - th(t_f) \quad (2)$$

In Eq. (1) Sb is the spring back at an integration point, $d(t_f)$ is the integration point displacement at the final time step after forming tools have been removed, and $d(t_{f-1})$ is the displacement at the end of the forming process but before the removal of the forming tools. In Eq. (2) T is the element value for thinning, $th(t_0)$ is the element thickness at the initial time step, and $th(t_f)$ is the element thickness at the final time step after the forming tools have been removed.

2. Forming limit diagram

Forming limit diagram (FLD) makes use of an element failure theory based on strain. This diagram is composed of a group of lines defining a region of safe combinations of major and minor element strains. If the element has major and minor strains that place it outside of this bounded zone, it is considered failed and unsafe. The FLD used in 3-dimensional optimization is presented in Fig. 3. This FLD was created from experimental data from Ref. 16. The major and minor strains were measured by using a grid marking scheme where the initial workpiece is marked with a uniform grid; after deformation, the grid is measured to determine the strain in each grid square. Manual inspection and recording of failed strain ratio results in a FLD used to determine element failure. For use in the MATLAB program, each of the bounding areas was fitted with an appropriate order curve. The equations for these curves are given as

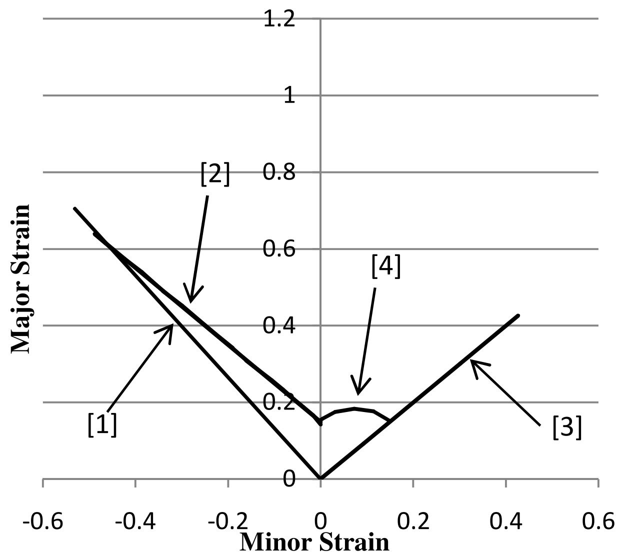


Figure 3. Experimental FLD for aluminum 6061-T6 alloy sheet[16].

$$M_jS = -1.326 * M_iS \quad (3)$$

$$M_jS = -1.005 * M_iS + 0.149 \quad (4)$$

$$M_jS = M_iS \quad (5)$$

$$M_jS = -5.652 M_iS^2 + 0.829 M_iS + 0.154 \quad (6)$$

where M_jS and M_iS represent the major and minor strains in an element respectively. Eqs. (3) to (6) represent the equations for lines 1 to 4 in Fig. 3 respectively. These equations are incorporated into the MATLAB program for checking the safety of each element at the end of forming using a logical loop.

3. Response averaging and constraint calculation

After the MATLAB file has extracted the relevant data, the information must be reduced into values applicable for use in optimization. The data for effective plastic stress, effective plastic strain, grain size, spring back, thinning, and damage is further processed to provide averages and maximum data points. This data is used to represent the general condition of the workpiece at the end of the simulation as well as the worst case elements in the workpiece. The average and maximum values are calculated as

$$Avg = \left(\sum_{i=1}^{n} \lambda_i\right)/n \quad (7)$$

$$Max = \max(\lambda_i) \tag{8}$$

In Eq. (7), Avg is the average value of a response over the entire workpiece, λ_i represents the response value at an integration point, and n represents the number of integration points in the workpiece. In Eq. (8), Max is the maximum value of the response λ_i. The use of both an average and a maximum in the optimization problem allows for the designer to control both the overall quality of the workpiece as well as the extreme values which could indicate localized problems in the product.

D. Optimization Code

The optimization code is responsible for examination of current design points and development of the next candidate set of parameters using a mathematical programming method. The paired suite of VisualDOC and VisualScript comprise the optimization code in this example optimization framework. VisualDOC is the optimization tool and VisualScript controls the flow of data and allows for communication with data files. The user must designate the locations of process parameters within the process simulation input files and the calculated response values within the MATLAB output file. These will be designated in VisualDOC as the design variables, constraints, and objectives for the optimization problem. All of the optimization options are selected within VisualDOC.

III. 2-Dimensional Process Based Sheet-Stamping Optimization Results

A pair of 2-dimensional optimization examples is presented to illustrate the basic operation of the optimization framework in the context of both a single-stage forming process and a multi-stage forming process. The first optimization problem is a single-stage sheet-stamping process and the second optimization problem is an example of a multi-stage sheet-stamping process.

A. 2-Dimensional Single-Stage Forming Simulation

The first example is a single stage forming process creating a C-Channel. The simulation was created using an aluminum alloy 6061-T6 blank with a thickness of 1.5 mm.

The principal interests in a part such as this one, seen in Fig. 4, are those of spring back, residual stress, thinning, and damage. The workpiece experiences large local plastic strains which results in residual stresses concentrating in the corners. Thinning can also occur in the corners of such a part caused by stretching which would imply a weakening of the part. In industry, this simple part would not pose a significant challenge as far as part quality is concerned. Because the baseline simulation was created with high quality, low damage, low spring back values, low amounts of thinning, and low residual stress, it was determined that this process would benefit most from an optimization to increase press speed.

This forming simulation was performed using the methods described previously. Since the simulation is only in 2-dimensions, FLD is not applicable to this problem. The optimization problem was set to maximize press speed while keeping the other responses near their baseline values to a tolerance of 0.001. The results of this optimization are shown in Table 1. It can be seen that the framework produced a significant increase in press speed without causing undesirable changes to the other process simulation responses. The optimized design produces an increase in press speed from 2 mm/s to 30 mm/s without violating the design constraints.

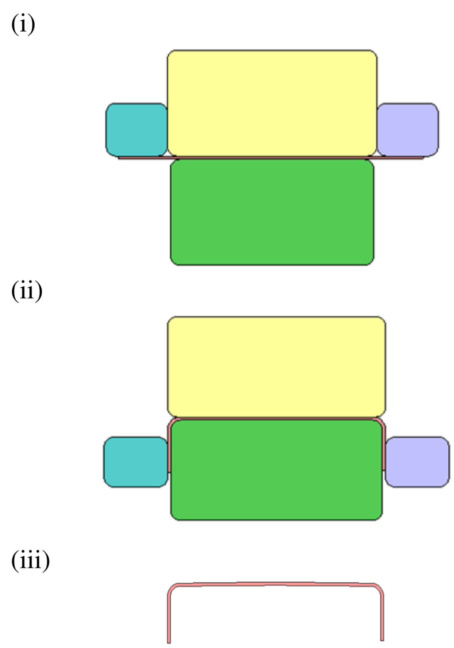


Figure 4. 2-Dimensional single-stage forming simulation.
(i) Simulation before forming
(ii) Simulation after forming, before tool release
(iii) Simulation after forming and tool release

Table 1. Single-stage sheet-stamping optimization results for AL6061-T6 C-Channel.

		Original	Optimized
Input	Friction (Coulomb)	0.3	0.25
	Press Speed (mm/sec)	2	30.01
	Die Temperature (K)	293.15	218.15
	Workpiece Temperature (K)	293.15	218.15
Responses	Y-axis spring back average (m)	9.79E-5	1.12E-4
	Y-axis spring back maximum (m)	2.27E-4	2.69E-4
	X-axis spring back average (m)	3.17E-6	3.16E-6
	X-axis spring back maximum (m)	1.36E-5	1.48E-5
	Thinning average (m)	5.64E-6	9.73E-7
	Thinning maximum (m)	6.74E-5	2.45E-5
	Residual stress average (Pa)	8.56E6	6.54E6
	Residual stress maximum (Pa)	6.20E7	5.70E7
	Damage average	1.79E-2	9.59E-3
	Damage maximum	0.3621	0.1922

B. 2-Dimensional Multi-Stage Forming Simulation

The second 2-dimensional example is a multistage forming process creating an axi-symmetric part. The simulation was created using an AL60601-T6 blank with thickness of 5.1 mm. Multistage processes are necessary to control large deformations across relatively small thicknesses. If the parts are formed in one pressing stage, fracture and undesired thickness variation may occur. The stages of this simulation are depicted in Fig. 5 rotated 180° to show part cross-section geometry. This simulation consists of two stages. Both stages have different press specifications, friction coefficients, and temperature profiles which can be altered in the optimization process. The two stages are linked together through their results files. Simufact.forming reads the input from the first file to set the beginning parameters for the second stage. The parameters imported into the second stage include damage, temperature, displacement, and strains for each element and integration point. This means that the internal responses and geometry changes occurring in the first stage are considered before beginning the next stage.

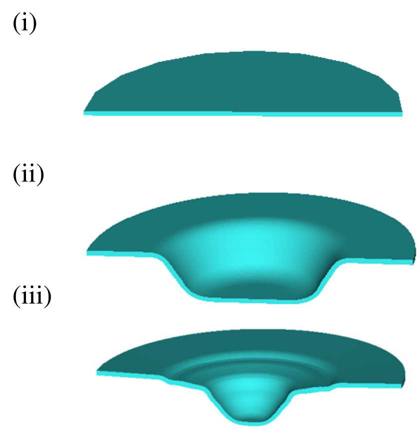


Figure 5. 2-Dimensional multi-stage forming simulation.
(i) Workpiece at the beginning of stage 1
(ii) Workpiece at the end of stage 1
(iii) Workpiece at the end of stage 2

This multi-stage process has been optimized using a multi-objective optimization scheme for maximum press speed for stages 1 and 2 combined. The constraints were formulated for the responses from the baseline simulation. Constraints were only placed on the results from the second forming stage since that represents the quality of the finished product.

The results from this optimization can be seen in Table 2. It can be seen that the optimization of this multi-stage process simulation was successful in increasing the combined objective of stage 1 and 2 press speeds combined without violating the constraints under the tolerance of 0.001.

Table 2. 2-dimensional multi-stage sheet-stamping optimization results for AL6061-T6 axi-symmetric model.

		Stage 1 Original	Stage 2 Original	Stage 1 Optimized	Stage 2 Optimized
Input	Friction (Coulomb)	0.01	0.01	0.0098	0
	Press Speed (mm/sec)	1	1	0.9456	19.16
	Die Temperature (K)	293.15	293.15	296.66	276.31
	Workpiece Temperature (K)	293.15	293.15	296.65	293.15
Responses	Average Y-axis Spring Back (m)	1.93E-4	2.5E-4	1.92E-4	2.72E-4
	Maximum Y-axis Spring Back (m)	4.18E-4	1.00E-3	4.15E-4	1.00E-3
	Average X-axis Spring Back (m)	9.47E-5	3.13E-5	9.41E-5	3.63E-5
	Maximum X-axis Spring Back (m)	2.14E-4	8.36E-5	2.12E-4	8.97E-5
	Average Thinning (m)	3.07E-4	-2.64E-4	3.07E-4	-2.67E-4
	Maximum Thinning (m)	9.78E-4	4.68E-4	9.77E-4	4.82E-4
	Average Damage	0.0929	0.1262	0.0928	0.1262
	Maximum Damage	0.3589	0.4079	0.3576	0.4065
	Average Effective Stress (Pa)	7.30E7	3.06E8	7.25E7	2.89E8
	Maximum Effective Stress (Pa)	4.26E8	5.54E8	4.20E8	5.46E8

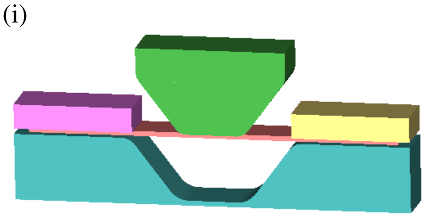
IV. 3-Dimensional Process Based Sheet-Stamping Optimization Results

This example was chosen to show the capabilities of the framework to handle 3-dimensional problems. The simulation was created to represent the sheet forming process of an angled hat section using a 2 mm thick AL6061-T6 blank as seen in Fig. 6. Three-dimensional simulations provide the design engineer a different approach to optimizing the part. With the inclusion of the third dimension, FLD can be used in the optimization.

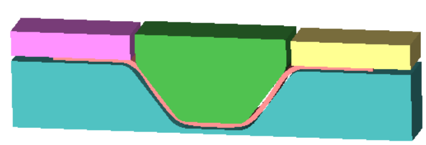
Three-dimensional simulation also poses a problem for computation time; these simulations take considerably more time to run than a similar 2-dimensional process simulation. To reduce the run time and complexity of the problem, a small section of the entire product was created. The workpiece was paired with a set of symmetry boundary conditions to create a fictitious full body. For this problem, a baseline simulation was created which was deemed unacceptable because of the large number of elements that failed under the FLD criteria. This unacceptable initial design point was used as the starting point for the simulation.

A synthetic variable was created to represent the failure rate of the elements in the workpiece. This variable is defined by Eq. (9) where $FailRate$ is the synthetic variable used as an objective function, F is the number of failed integration points in the workpiece, and Tot is the total number of

(i)



(ii)



(iii)

Figure 6. 3-dimensional forming simulation.
(i) Simulation before forming
(ii) Simulation after forming before tool release
(iii) Simulation after forming and tool release

integration points in the workpiece. The element failure rate was chosen as the objective function since it was the aspect of the simulation that needed the most improvement.

$$FR = F/(Tot) \tag{9}$$

The optimization was set up to minimize the failure rate with constraints on the damage, spring back, and thinning. Table 3 contains the results of this 3-dimensional optimization. It can be seen that the optimization framework correctly handled the 3-dimensional problem and reduced the failure rate of the elements from 15% to 13% while avoiding violating the constraints set by the baseline simulation. Although with 13% of the elements failed, this product would likely be defective; this is a successful demonstration of the optimization scheme applied to a 3-dimensional problem.

Table 3. 3-dimensional optimization results for AL6061-T6 angled hat stringer.

		Original	Optimized
Input	Friction (plastic)	0.6	0.1387
	Press Speed (mm/sec)	1	2.17
	Die Temperature (K)	293.15	391.37
	Workpiece Temperature (K)	293.15	325.72
	Ambient Temperature (K)	293.15	360.28
Responses	Y-axis spring back average (m)	3.64E-5	2.61E-5
	Y-axis spring back maximum (m)	4.08E-4	3.94E-4
	X-axis spring back average (m)	3.64E-5	2.63E-5
	X-axis spring back maximum (m)	4.08E-4	3.95E-4
	Thinning average (m)	6.12E-6	1.07E-6
	Thinning maximum (m)	5.47E-5	4.00E-5
	Failure Ratio	0.1557	0.1369
	Damage average	7.83E-3	7.16E-3
	Damage maximum	0.4651	0.3149

V. Conclusions and Future Work

This paper described the development and implementation of a generalized framework for sheet-forming process simulation and optimization. The framework was then integrated with a set of example software packages to successfully optimize three different process simulations. The versatility of the framework to handle the complexity of sheet-stamping processes was shown through single-stage, multi-stage, 2-dimensional, and 3-dimensional examples. This optimization framework can prove useful for any software used as the three main tool, process simulation, optimization code, and response filtering. Future work in the realm of this optimization framework include the implementation of a detailed microscale material model and implementation of the framework on detailed 3-dimensional simulation and optimization of complex sheet-formed automotive parts. Work is currently underway to produce both an automotive bumper and side-rail using the prescribed optimization framework. The inclusion of these automotive parts was limited, not by the capabilities of the developed tool, but by computation time required to perform an optimization on a large 3-dimensional body.

Acknowledgments

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