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MULTI-OBJECTIVE DESIGN OPTIMISATION OF A 3D-RAIL STAMPING PROCESS USING A ROBUST MULTI-OBJECTIVE OPTIMISATION PLATFORM (RMOP)

DONGSEOP LEE[†], MARTÍ COMA*, HÉCTOR ESPINOZA[‡], OSCAR FRUITOS[§] AND JORDI PONS-PRATS[¤]

[†] International Center for Numerical Methods in Engineering (CIMNE)
Parc Mediterrani de la Tecnologia, UPC
Esteve Terrades 5, Building C3, 08860 Castelldefels, Spain
e-mail: ds.chris.lee@gmail.com, web page: http://www.cimne.com

[*] International Center for Numerical Methods in Engineering (CIMNE)
Parc Mediterrani de la Tecnologia, UPC
Esteve Terrades 5, Building C3, 08860 Castelldefels, Spain
e-mail: mcoma@cimne.upc.edu, web page: http://www.cimne.com

[‡] International Center for Numerical Methods in Engineering (CIMNE)
Campus Norte UPC, Building C1, Of. 102, 08034 Barcelona, Spain
e-mail: hespinoza@cimne.upc.edu, web page: http://www.cimne.com

[§] International Center for Numerical Methods in Engineering (CIMNE)
Parc Mediterrani de la Tecnologia, UPC
Esteve Terrades 5, Building C3, 08860 Castelldefels, Spain
e-mail: metalform@cimne.upc.edu, web page: http://www.cimne.com

[¤] International Center for Numerical Methods in Engineering (CIMNE)
Parc Mediterrani de la Tecnologia, UPC
Esteve Terrades 5, Building C3, 08860 Castelldefels, Spain
e-mail: jpons@cimne.upc.edu, web page: http://www.cimne.com

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Abstract.

The paper investigates the multi-objective design optimisation of a stamping process to control the final shape and the final quality using advanced high strength steels. The design problem of the stamping process is formulated to minimise the difference between the desired shape and the final geometry obtained by numerical simulation accounting elastic springback. In addition, the final product quality is maximised by improving safety zones without wrinkling, thinning, or failure. Numerical results show that the proposed methodology improves the final product quality while reduces its springback.

1. INTRODUCTION

Sheet metal forming is a very important manufacturing process because of its ability to obtain complex shapes. The final product quality is measured in terms of springback and safety. One important challenge in manufacturing is to guarantee the final product quality while controlling the final shape. In particular, for stamping processes, numerical simulations are commonly used for designing a part to ensure that it is possible to arrive to the final desired shape without too much stress (failure zone), without too small material thickness (thinning zone) or without wrinkles (wrinkling zone) [1, 2].

Advanced High Strength Steels (AHSS) have been focused recently in the automotive industry. AHSS has superiority of the strength to weight ratio that improves fuel efficiency and crashworthiness assessment of vehicles. However, the major drawback of the automotive structural member with AHSS is the tendency of large springback due to their high yield strength.

Some work has already been done in the field of stamping optimization. There is a research work that couples a Finite Element Code with optimization methods such as surface method, moving least squares and Pareto optimal solutions [3]. They describe a methodology to reach an optimal solution for both multi-objective and single objective optimization processes.

Additionally, there is manufacturing optimization applied to stamping processes that focuses on the tool configuration and takes into account friction generated noise using genetic algorithms [4]. Furthermore, process variability can be considered to produce a robust design methodology.

Moreover, the double-bend technique has been successfully applied to optimize springback in a U-Channel application [5]. In addition, sheet thickness, material properties and blank dimensions have been used as design variables to optimize springback in automotive applications [6 -9].

In this paper a computational intelligence system RMOP developed at CIMNE [10 -12] and a Finite Element Analysis (FEA) software are coupled to reduce springback and to maximize product quality.

The paper is organized as follows: Section 2 describes the methodology followed. Section 3 presents the Finite Element stamping analyser (Stampack) [13]. In Section 4 two stamping process design optimization are conducted. Finally, in section 5 conclusions are drawn.

2. METHODOLOGY

2.1 Multi-Objective Design Optimisation

Often, engineering design problems require a simultaneous optimisation of conflicting objectives and an associated number of constraints. Unlike single objective optimisation problems, the solution is a set of points known as Pareto optimal set. Solutions are compared to other solutions using the concept of Pareto dominance. A multi-criteria optimisation problem can be formulated as:

Maximise/Minimise

$$f_i(\boldsymbol{x}),\ i = 1, \dots, N_f, \tag{1}$$

Subject to constraints:

$$g_j(\boldsymbol{x}) = 0 \text{ and } h_k(\boldsymbol{x}) \geq 0,\ j = 1, \dots, N_g,\ k = 1, \dots, N_h, \tag{2}$$

where f_i g_j h_k are, respectively, the objective functions, the equality and the inequality constraints, $\boldsymbol{x}$ is an N_x dimensional vector where its arguments are the decision variables. For a minimisation problem, a vector $\boldsymbol{x}_1$ is said partially less than vector $\boldsymbol{x}_2$ if:

$$\forall i\ f_i(\boldsymbol{x}_1) \leq f_i(\boldsymbol{x}_2) \text{ and } \exists j\ f_j(\boldsymbol{x}_1) < f_j(\boldsymbol{x}_2), \tag{3}$$

In this case the solution $\boldsymbol{x}_1$dominates the solution $\boldsymbol{x}_2$.

As Genetic Algorithms (GAs) evaluate multiple populations of points, they are capable of finding a number of solutions in a Pareto set. Pareto selection ranks the population and selects the non-dominated individuals for the Pareto fronts. A Genetic Algorithm that has capabilities for multi-objective optimisation is termed Multi-Objective Genetic Algorithms (MOGAs). Theory and applications of MOGAs can be found in References [10 -12].

2.2 Robust Multi-objective Optimisation Platform (RMOP)

For the optimization, the Multi-Objective Genetic Algorithm (MOGA) module in RMOP developed at CIMNE is utilized to minimize global springback and to maximize global safety zone under distributed/parallel computing environment. Details of RMOP can be found in references [10 -12]. The design variable taken into account is the holding force during the forming stage.

3. STAMPING ANALYSIS TOOL: STAMPACK

The stamping process is simulated using Stampack v.6.2.5 from QUANTECH ATZ [13]. Stampack is an explicit, advanced, multipurpose and multistage simulation software based on FEA. It's oriented to automotive, aeronautics/aerospace, transport, and metal packaging.

Stampack offers a library of solid, beam and shell finite elements based on the latest and best formulations developed at CIMNE as well as those adapted from scientific literature. Different types of elements can be mixed in a model and special constraints are available to connect solid elements to beam and shell elements and to link beam with shell elements. Initial conditions for displacements and velocities can be specified and structural damping can be included in the analysis. The time integration is performed by the central difference explicit method using automatic time stepping if required. The program has interfaces to a geometric modeller and pre-processor enabling the easy creation of the geometry and applying the conditions, constraints and properties, as well as to a graphical post-processor with which the results can be quickly seen. The program has been validated on a large number of test and industrial examples in which very good performance and efficiency have been shown [16].

In this paper, the forming process is started from a flat blank, without considering draw beads, through reproducing the forming stage and then finally simulating springback effect. The blank is discretized with Basic Shell Triangle (BST) consisting three-node triangular shell elements [14] and a penalty contact algorithm is implemented. An elasto-plastic material model is used with anisotropic plane stress hypothesis based on Hill's theory in plastic part. The viability and quality of the process determination is based on metal failure, wrinkling and springback analysis.

Hill's Theory

Rodney Hill proposed his first yield condition theory in 1948 to take into account anisotropy [15]. It is basically a generalization of the Von Mises yield condition which is isotropic. The 90 Hill's yield criterion [17] is used to model the plastic zone of the steels considered in this work.

Hardening

Hardening is the strengthening of a metal by plastic deformation. Some materials like Carbon steel generally get stronger when subjected to plastic deformation but with specific behaviours in function of alloy and thermo mechanic treatment of fabrication or preprocessing press. Some materials loose strength when deformed plastically (this is known as softening).

Several mathematical models are used to model these behaviours. In the present work, we have used two hardening models: Ludwik-Nadai model and the Voce model.

Ludwik-Nadai Hardening Model

It is a non-linear hardening model which approximates the plastic stress as a constant times the total strain with an exponent.

$$\sigma = C(\varepsilon_0 + \varepsilon_p)^n, \quad (4)$$

Where C is the Ludwik constant, n is the hardening exponent, ε_p is the plastic strain, ε_0 is the strain needed to reproduce the yield stress when there is not plastic strain.

Voce Hardening Model

It is a hardening model that considers saturation of the hardening. That is the strength does not increase indefinitely, but reaches a maximum value in an asymptotic regime.

$$\sigma = A - Be^{-c\varepsilon_p}, \quad (5)$$

Where A is the saturation stress, $A - B$ is the yield stress and c is an exponential constant.

4. MULTI-OBJECTIVE DESIGN OPTIMISATION OF STAMPING PROCESS

4.1 Formulation of Problem

The stamping process design problem consists in a 3D S-Rail stamping based on a benchmark problem of NUMISHEET 1996 conference [18]. This problem is non-linear and discontinuous; therefore, the implementation of optimisation is essential for effective manufacturing. Figure 1 and Table 1 show the schematic view of tools and their dimensions in 2D and 3D.

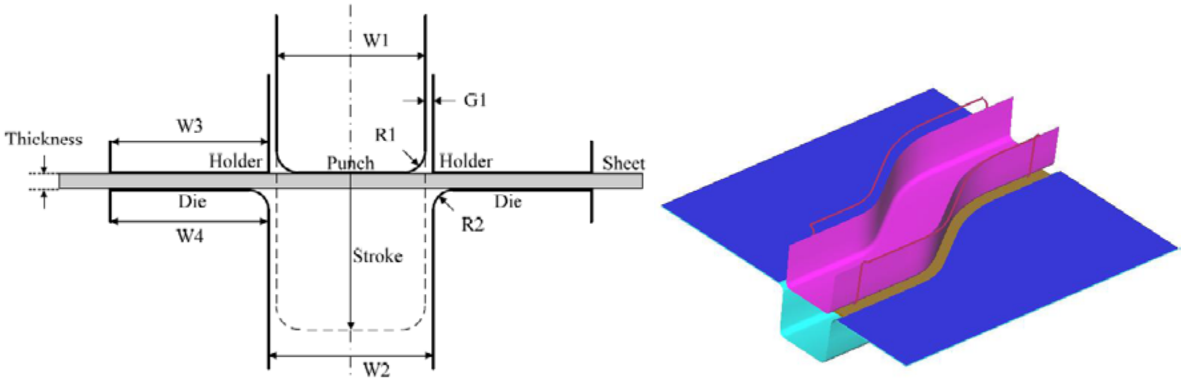

Figure 1. Schematic view of tools and sheet for drawing test in 2D (left) and 3D (right).

Table 1. Dimensions for the drawing test tools (mm).

Parameters	W1	W2	W3	W4	R1	R2	G1	Stroke
Dimensions	45	50	122	127	5	5	2	40

In this case a High Strength Steel with Ludwik- Nadai hardening model is considered and the material characteristics are shown in Table 2.

Table 2. Material (Steel) properties: HSS

Properties	Young's Modulus (GPa)	Poisson ratio	Density (Kg/m^3)	Yield Strength (MPa)
HSS	210	0.3	7800	680

For the numerical simulation, a 3D model with shell elements is used without considering draw beads. For the optimization, the Genetic Algorithm (GA) module in RMOP is utilized to minimize global springback (stage displacement) and to maximize global safety (see Table 3). The design variable taken into account is the holding force during the forming process.

Table 3. Safety range.

Range	0.5 -1.5	1.5 -2.5	2.5 -3.5	3.5 -4.5	4.5 -5.5	5.5 – 6.5	6.5 -7.5
Safety Factor	Strong Wrkl	Wrinkling	Low Strain	Safe	Marginal	Thinning	Fail

4.2 Multi-objective Single-Holding Process Design Optimisation without Final Cutting

Problem Definition

This test case is a multi-objective design optimisation of single-holding process using RMOP coupled to Stampack version 6.2.5. The objectives are to minimise global springback (6) and to obtain a global safety factor near 4 (7).

$$f_1 = D_G = \frac{1}{\text{npoin}} \sum_{\text{ipoin}=1}^{\text{npoin}} D_{\text{ipoin}} \quad \text{(Global/average stage displacement)}, \qquad (6)$$

$$f_2 = S_G = \frac{1}{\text{nelem}} \sum_{\text{ielem}=1}^{\text{nelem}} |4 - S_{\text{ielem}}| \quad \text{(Global/average safety factor)}, \qquad (7)$$

where D_{ipoin} and S_{ielem} represent the local springback (Euclidean norm of the springback vector) and the local safety factor at each point of the discretization and at each element respectively. The discretization has npoin=4599 and nelem=8944.

The reason why D_G and S_G is considered over all the surface instead of only one control point (conventional) is to make sure that the optimal design has lower springback and higher safety factor all over the physical model especially on the objective area.

Numerical Results: Single-Holding Process

The optimization ran for 20 hours with 180 function evaluations in 10 threads of an Intel 3.6GHz processor. Figure 2 shows the Pareto optimal front obtained by RMOP. It can be seen that the optimization process produces lower springback and better safety factor. Pareto optimal members 1 (the best solution for springback), 7 (compromise solution) and 18 (the best solution for safety factor) are selected and compared to the *baseline design* (B).

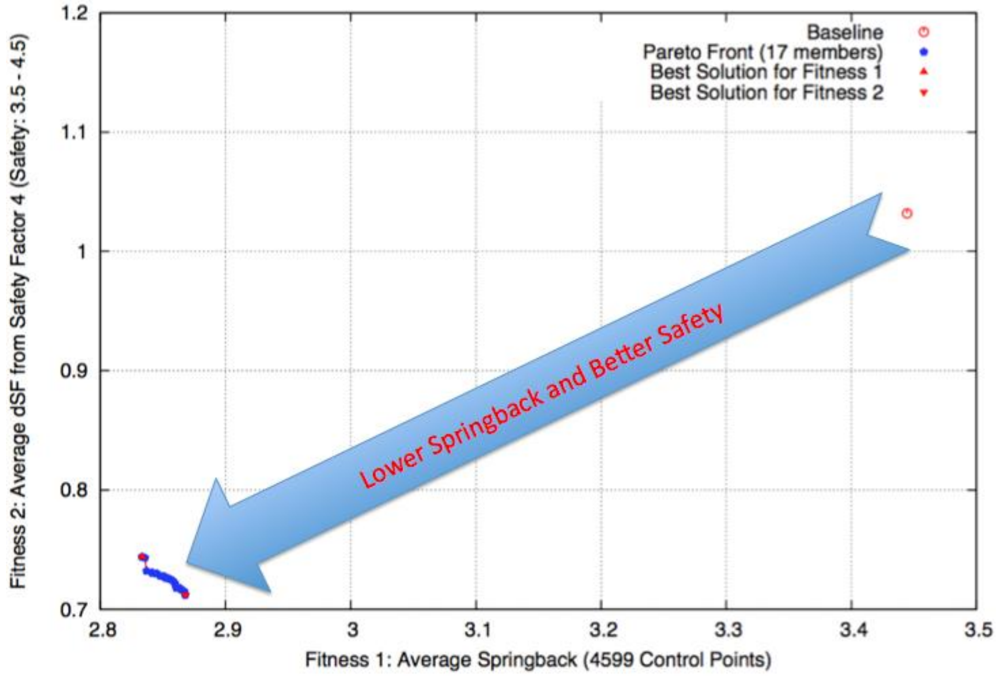

Figure 2. Pareto optimal front compared to the baseline design for S-Rail single-forming process.

Table 4 compares the fitness values obtained by B and the Pareto optimal solutions and also illustrates the optimal force factors obtained for the holding and forming process. Even though the optimal solutions have high force factor during the holding and forming, they reduce f_1 by more than 16% and f_2 by more than 28% with respect to B. The main reason why the optimal solutions have higher force factor is that the physical model did not take into account of the draw beads between holder and die. Figure 3 shows stamping process curves for B and Pareto members 1, 7 and 18.

Table 4. Comparison of D_G and S_G for the baseline design and Pareto optimal members 1, 7 and 18.

Models	D_G *(mm)*	S_G	**Force Factor (Holding)**	**Force Factor (Single-Forming)**
Baseline	3.445	1.032	1.00	1.00-1.00
Pareto M1	2.833 (- 18.0%)	0.743 (- 28.0%)	1.00	7.14-9.55
Pareto M7	2.847 (- 17.2%)	0.728 (- 29.4%)	1.00	9.19-9.33
Pareto M18	***2.867 (- 16.7%)***	***0.712 (- 31.0%)***	***1.00***	***9.23-9.92***

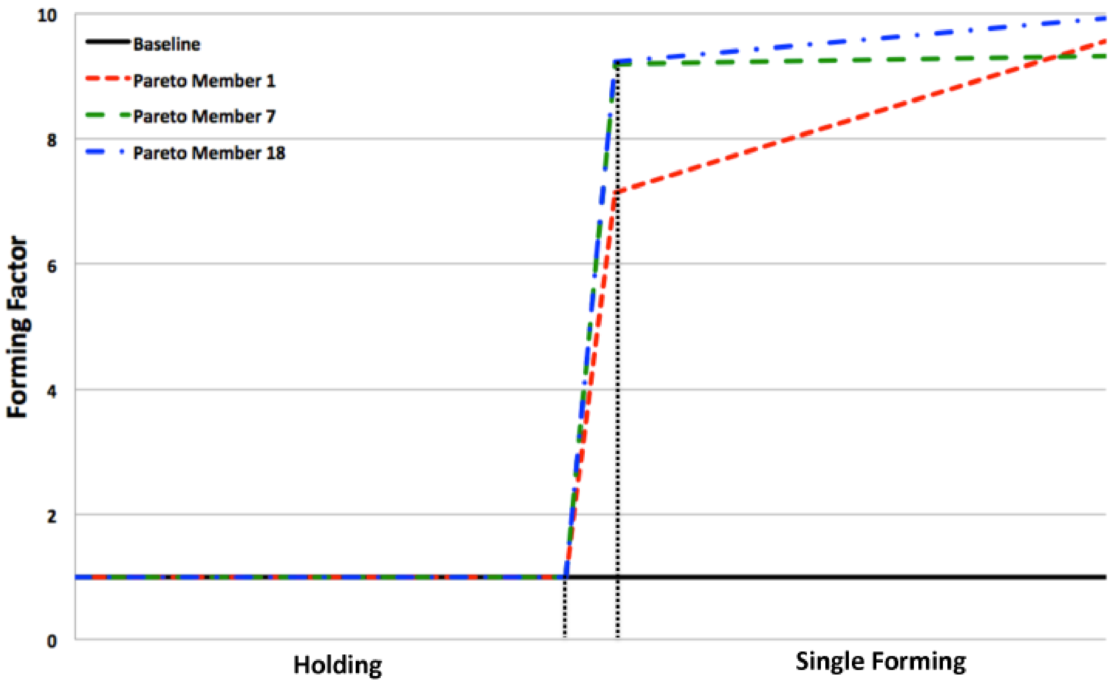

Figure 3. Stamping process curves for the baseline design, Pareto members 1, 7 and 18.

Figure 4 compares the springback obtained for B and M18 (the best solution with respect to S_G). It can be seen that M18 keeps the shape after forming while the baseline design tries to springback to the original shape. As consequence, M18, with a maximum springback of $D = 6.82$ mm, has 20% lower local maximum when compared to B (max $D = 8.43$ mm).

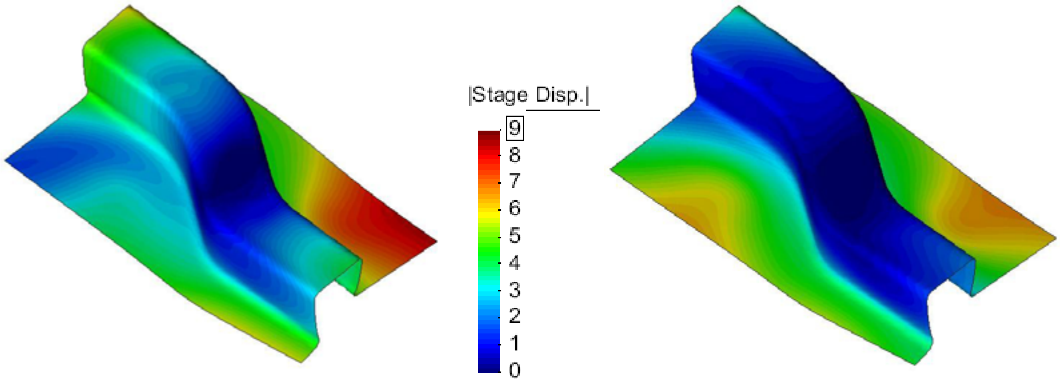

Figure 4. Springback contour (scale in mm) for B (left) and M18 (right)

Figure 5 compares the safety factor obtained for B and M18. It can be seen that M18 does not have any strong winkling (zone 1), has less winkling (zone 2) and has a bigger safety zone in the objective area.

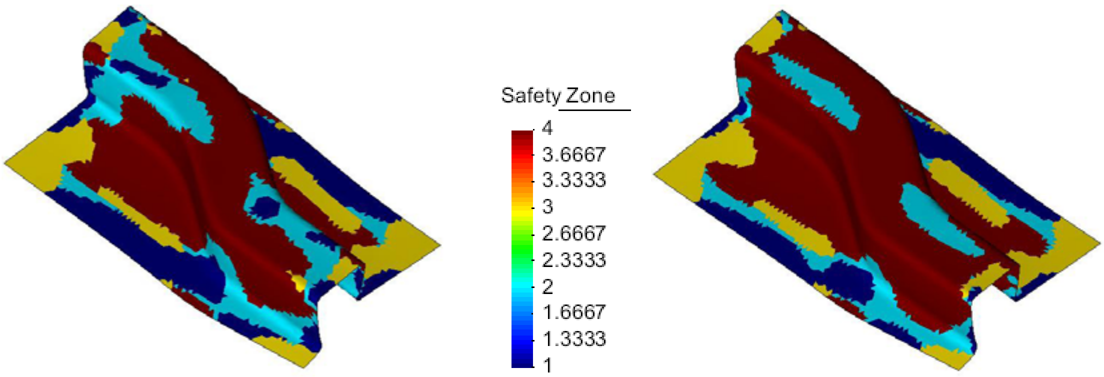

Figure 5. Safety factor contour for B (left) and M18 (right).

4.3 Multi-objective Multi-Forming Process Design Optimisation with Final Cutting

Problem Definition

This test case is a multi-objective design optimisation of multi-forming process using RMOP coupled to Stampack version 6.2.5. During the optimisation, multi-forming and final cutting process are implemented that may result in improvement of safety zone. The main reason for applying multi-forming process is that controlling holding force during multi-forming can improve S_G of the final product.

The objectives are to minimise global springback (D_G) and to maximise global safety factor (minimise S_G) after the final cutting process. The same fitness functions (Equations (6)and (7)) are considered as in Section 4.2.

Numerical Results

The optimization ran for 50 hours with 1100 function evaluations in Intel 10 × 3.6GHz processor. Figure 6 shows the Pareto optimal front obtained by RMOP. It can be seen that all Pareto optimal solutions dominate the baseline design while producing lower springback and better safety factor. Pareto optimal members 1 (the best solution for springback), 7 (compromised solution) and 12 (the best solution for safety factor) are selected and compared to the baseline design.

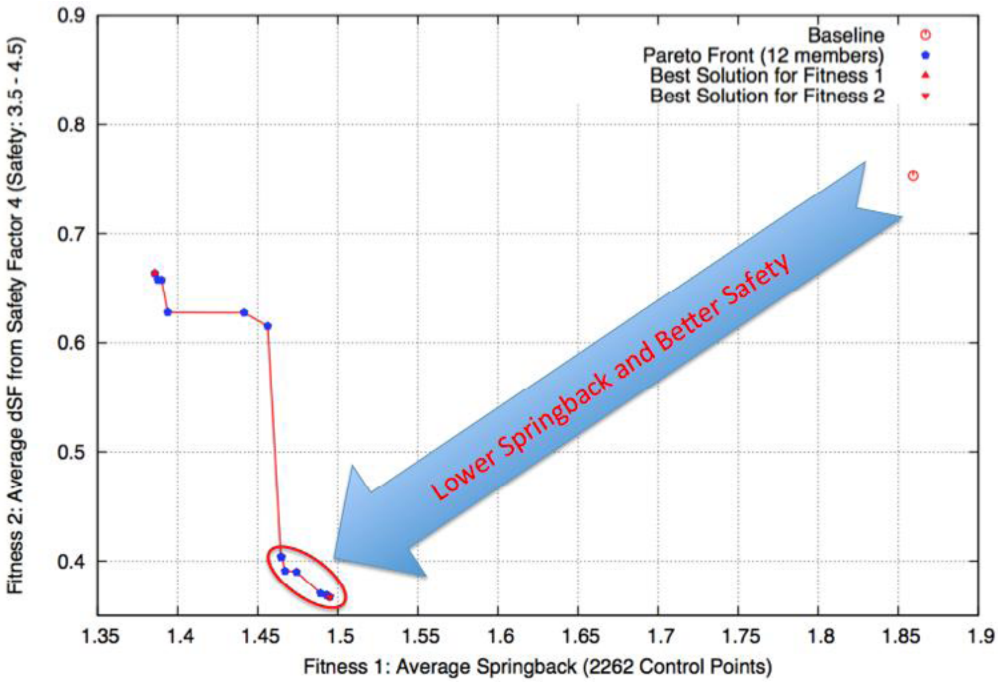

Figure 6. Pareto optimal front compared to the baseline design for S-Rail multi-forming process.

Table 5 compares the fitness values obtained by the baseline design and Pareto optimal members 1 (the best solution for global springback), 7 (compromised solution), 12 (the best solution for global safety) and also illustrates the optimal force factors during the holding and multi-forming process. Even though Pareto member 7 (compromised solution) has high force factor during the holding and forming, it reduces the springback by more than 21% and more than 46% closer to the perfect safety factor 4 when compared to the baseline design. Figure 7 shows the stamping process curves obtained by the baseline design, Pareto members 1, 7 and 12. It can be noticed that Pareto member 1 (the best solution for global springback) has lower holding force during forming processes 1 and 2 and then high holding force while Pareto member 12 (the best solution for global safety) has high holding force factors during all forming processes.

Table 5. Comparison of D_G and S_G for the baseline design and Pareto optimal members 1, 7 and 12.

Models	**D_G (mm)**	**S_G**	**Force Factor (Holding)**	**Force Factor (Forming-I)**	**Force Factor (Forming-II)**	**Force Factor (Forming-III)**
Baseline	1.860	0.753	1.00	1.00	1.00	1.00
Pareto M1	1.385 (- 25.5%)	0.664 (- 12.0%)	1.00	1.99	0.13	9.91
Pareto M7	*1.464 (- 21.3%)*	*0.404 (- 46.3%)*	*1.00*	*3.13*	*9.96*	*8.98*
Pareto M12	*1.495 (- 20.0%)*	*0.366 (- 51.0%)*	*1.00*	*9.92*	*9.95*	*9.95*

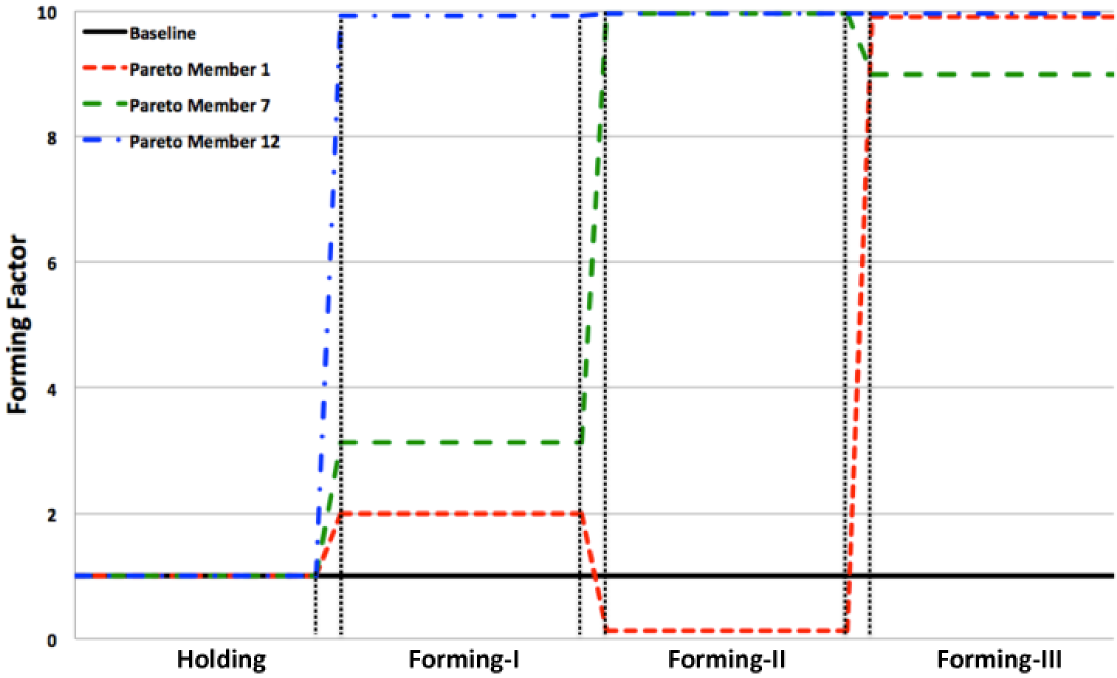

Figure 7. Stamping process curves for the baseline design and Pareto members 1, 7 and 12.

Figure 8 compares the stage displacement (springback) obtained by the baseline design and Pareto optimal member 12 (the best solution for global safety) in 3D isometric view. It can be seen that Pareto member 12 maintains the shape of objective area (S-Rail part: blue – close to 0 mm) with lower stage displacement even after stamping while the baseline design tries to springback to the original shape. As consequence, Pareto member 12 (max local displacement of 6.13 mm) has 8% lower local max displacement when compared to the baseline design (max local displacement of 6.68 mm).

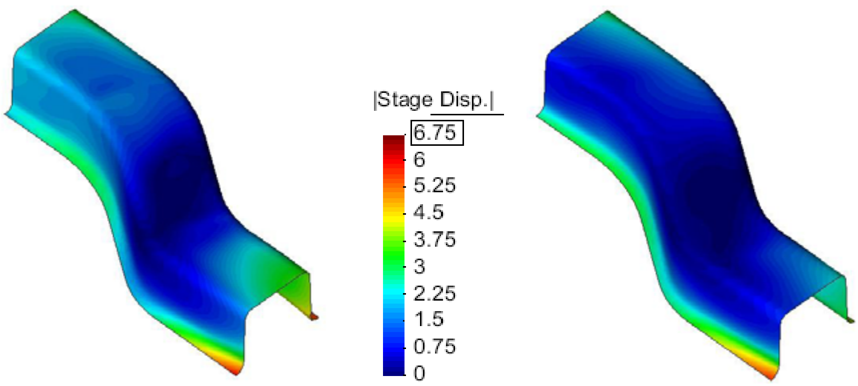

Figure 8. Springback contour (scale in mm) obtained for B (left) and M12 (right).

Figure 9 compares the safety factor contour obtained by the baseline design and Pareto member 12 (the best solution for global safety). It can be seen that Pareto member 12 removes all strong winkling on the top of S-Rail while increasing safety zone in objective area but the baseline design has strong winkle over the objective area.

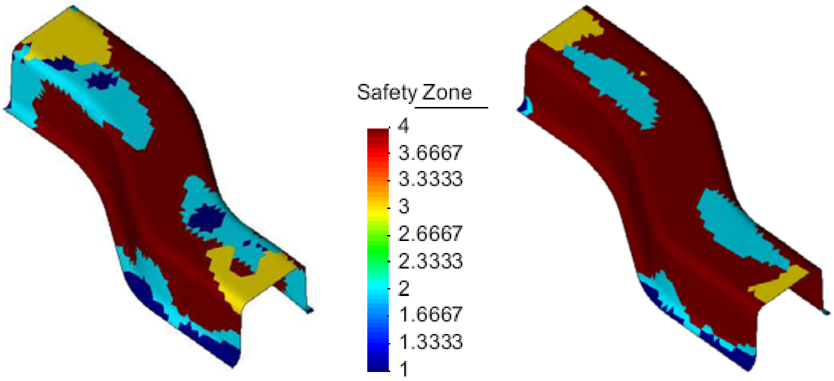

Figure 9. Safety factor contour obtained for B (left) and M12 (right).

CONCLUSION

In this paper, a methodology for single-forming and multi-forming design optimisation of S-Rail has been described and investigated. The methodology couples a robust multi-objective evolutionary algorithm and a finite element based stamping analysis tool under a parallel computing system. It has been implemented to improve the quality of final products in terms of both the global springback and the global safety factor. Analytical research shows that Pareto optimal solutions obtained from the optimisation offers a set of selections to design engineers so that they may proceed into more detail phases of the stamping design process. Future work will focus on the detailed design optimisation of a stamping process including draw beads shape and initial cutting for automobile parts.

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