

Robust Optimization of Drawbead Forces for a B-pillar Stamping

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ABSTRACT

Many uncertainties exist in the sheet metal stamping such as the variation of incoming material properties, die and press setup conditions, long-term tool wear and degradations. They are interacting in a way to make the process less robust, thus contributing to increased scrap rates and more unscheduled downtime. This paper presents a new approach for the die design optimization where these uncertainties are taken into account. A Tailor-Welded B-pillar consisting of 1.65mm DP600 and 0.9mm DDQ is selected as the focal part to demonstrate the new design process. The study is divided into two phases. The focus of the first phase is to understand the complexity of the formability window and determine effective optimization techniques under deterministic conditions. It is found that the formability window is highly nonlinear, or even discontinuous if a global objective function such as the Maximum Failure Factor is used. It is therefore more advantageous to adopt a regional approach where the split-prone zones and wrinkle-prone zones are identified. Optimization can then take place for each region with a multi-objective approach using the Non-dominated Sorting Genetic Algorithm (NSGA-II). The second phase takes into account the stamping uncertainties, and both the formability values and their deviations are optimized

simultaneously for robustness. It is demonstrated that the robust optimization under uncertainties is able to reduce output variability while maintaining the same level of "optimal" performance as compared with deterministic optimization.

INTRODUCTION

Sheet metal stamping is a complex manufacturing process subject to many engineering considerations and noise factors. Uncertainties such as the variation of incoming material properties, die and press setup conditions, long-term tool wear and degradations are all interacting in a way to make the process less robust, thus contributing to increased scrap rates and unscheduled downtime which cost automotive OEMs and stamping suppliers hundreds of millions of dollars annually. Great efforts have been made at manufacturing plant level to monitor and control the stamping process in order to increase its robustness. At the same time, sheet metal producers have been making great strides to tighten the variability of mechanical properties of supplied materials from coil-to-coil, batch-to-batch, and plant-to-plant by investing in new process technologies and control methods. However, a systematic approach has yet to take place where both manufacturing process and material property

variations are incorporated in the die engineering process, and a most robust design can be reached under all considered uncertainties. Current practice of stamping design optimizations is not concerned about process robustness, and stamping simulations are used primarily to validate whether or not a design has any potential formability issues such as splits and wrinkles under a set of nominal conditions.

Tailor-Welded Blanks (TWB), where two sheet metal blanks with different grades and/or thicknesses laser-welded into a single piece for stamping, have found wide applications on vehicle body structures over the past decade [1-3]. They offer targeted performance with improved material utilization and greater weight-saving opportunities. Recently their usage is extended to Advanced High-Strength Steels (AHSS) such as DP600 for crash-critical components. A Tailor-Welded Blank design with AHSS joined by mild steels poses many particular challenges to stamping engineering and manufacturing. On one hand, the significant differences in their strengths and formability alter the material flow during stamping in a way much harder to predict. On the other hand, Advanced High-Strength Steels tend to exhibit greater variability in mechanical properties due to their complex microstructures and manufacturing processes. As a result, the robustness of die engineering becomes even more important.

This paper presents a new approach in the die design where the uncertainties are taken into account. Such design and optimization provide a means to make sure that unacceptable failures are unlikely to occur with an acceptable confidence [4-7]. A Tailor-Welded B-pillar with 1.65mm DP600 and 0.9mm DDQ is selected as the focal part to demonstrate the new design process.

The study is divided into two phases. The focus of the first phase is to establish stamping formability window and optimize the design accordingly under deterministic conditions. The formability window is a hyper-domain in the design space where neither splits nor wrinkles occur. The design parameters are drawbead locations and strengths as they control material in-flow. An Optimal Latin Hypercube Sampling (OLHS) technique is employed to construct a series of Design of Experiments (DOE), and optimization results are obtained by the Kriging method using the Multi-island Genetic Algorithm. It is found that the formability window is highly nonlinear, and a refined design set has to be constructed, followed by the establishment of a sequential surrogate model based on neural network method. A multi-objective optimization is then pursued by using the Non-dominated Sorting Genetic Algorithm (NSGA-II), which is believed to be particularly effective for discontinuous design spaces.

The second phase takes into account of the uncertainties of incoming material properties. Statistical data of material properties are obtained from an extensive collection of mechanical testings for both DDQ and DP600 steels. The data of interests are forming related parameters such the material hardening exponent n values, anisotropy R values, and the initial yield strengths. Their statistical representation is added in the simulation model as noise variables, and the robust optimization is conducted in two ways to offer a comparison. In the first case, only the formability values are optimized and a set of optimal design variables are obtained. Monte Carlo simulations are then conducted for the surrogate model with the obtained "optimal" design and with statistical variations of the noise variables, which gives the statistical characterization of the formability values, i.e., the robustness of the "optimal" design as represented by the standard deviation. In the second case, however, both the formability values and their standard deviations are optimized, which is truly a robust optimization. The comparison of the two sets of obtained results demonstrate that the robust optimization is able to reduce formability variations significantly while maintaining roughly the same or slightly better level of formability values.

TAILOR-WELDED B-PILLAR MODEL

DRAW DEVELOPMENT

The methodology developed in this paper for die design optimization and robustness is quite general in its approach. A Tailor-Welded B-pillar shown in Fig. 1 is selected as the focal part to demonstrate the approach. It consists of DP600 of 1.65mm thick for the upper and DDQ of 0.9mm for the lower. The design provides efficient energy management during a crash event. The mechanical properties of both DP600 and DDQ steels are listed in Table 1, which will be used for numerical simulations in the study.

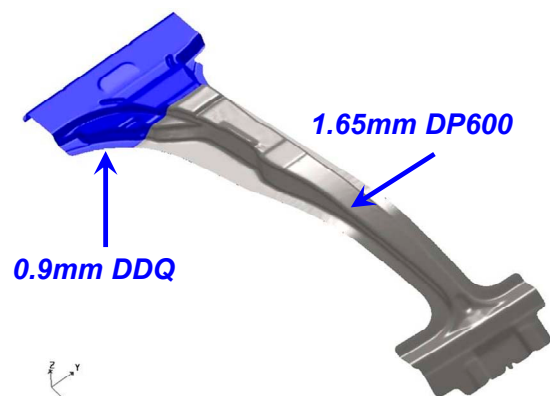


Figure 1. A Tailor-Welded B-Pillar

Table 1. Mechanical Properties of the Sheet Metals

Material	DDQ	DP600
Thickness (mm)	0.9	1.65
Yield stress (MPa)	174	412
Tensile stress (MPa)	320	643
Hardening Exponent (n-	0.2	0.14
Anisotropy Parameter R_0	1.92	1.16
Anisotropy Parameter R_{45}	1.30	0.67
Anisotropy Parameter R_{90}	2.08	1.17
$R = \frac{R_0 + 2R_{45} + R_{90}}{4}$	1.65	0.92

Drawbead design is an integral part of draw development process in die face engineering. By controlling drawbead restraining forces (DBRF), die engineers can effectively optimize material flow in order to achieve desired formability [8-11]. For a complex part such as the B-pillar in Fig. 1, drawbeads are divided into many segments, and the optimization of their locations and strengths becomes very critical. Fig. 2 is the base design for the drawbead development of the B-pillar, where it consists of 17 drawbead segments. Fig. 3 is the corresponding tailor-welded blank shape. In the traditional draw development process, the drawbead strengths of each segment are assigned based on an engineer's experience. Stamping simulations are then conducted to determine whether or not the design meets formability requirements of no splits and no wrinkles. If the part is deemed infeasible, drawbead strengths are adjusted until a satisfactory solution set is found.

MAXIMUM FAILURE FACTOR

The Forming Limit Diagram (FLD) as pioneered by Keeler and others [12-14] has been widely used to assess sheet metal failure due to localized necking in sheet metal forming process. In this formulation, a single Forming Limit Curve (FLC) of in-plane limit major strain versus minor strain is served as the forming limit

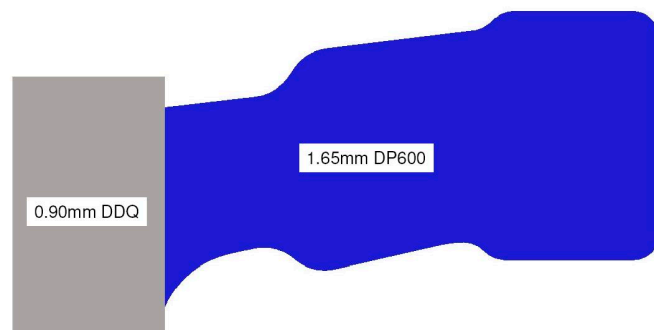


Figure 3. Blank Development for the TWB B-Pillar

criterion, beyond which the sheet metal is deemed to fail by starting localizing. The formability assessment is usually presented in qualitative terms: red when the part is deemed not feasible; yellow when the part is probably feasible; and green when there are no issues of concern. However for optimization and robustness studies, the formability must be quantified. To this end, the concept of Maximum Failure Factor is adopted in this study to quantify the likelihood of sheet metal formability [15].

Firstly, the Failure Factor, F , is defined as the ratio of the major strain at any material point to the major strain on the Forming Limit Curve (FLC) corresponding to the same minor strain value. It is given by, as illustrated in Fig. 4,

$$F = \frac{\epsilon_{major}}{\epsilon_{major}^{FLC}} \quad (1)$$

For $F > 1$, the deformation exceeds the forming limit and the material is likely to split. Conversely if $F < 1$, the material is likely to be safe. The smaller the F value, the better the design will be. The strain signatures shown in Fig. 4 is the result for the DDQ portion of the B-pillar stamping. It becomes apparent that the adoption of Failure Factor is even more crucial for the evaluation of tailor-welded blanks due to the different forming limit curves of each of the steel grades.

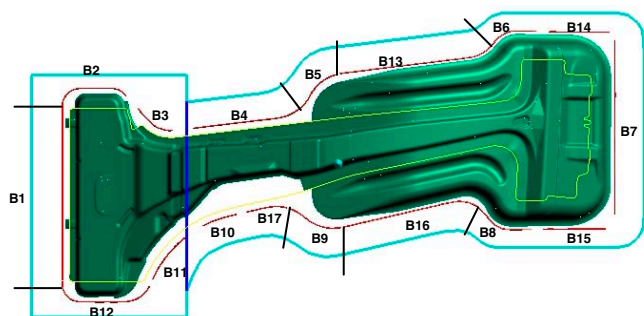


Figure 2. Drawbead Development for the TWB B-Pillar

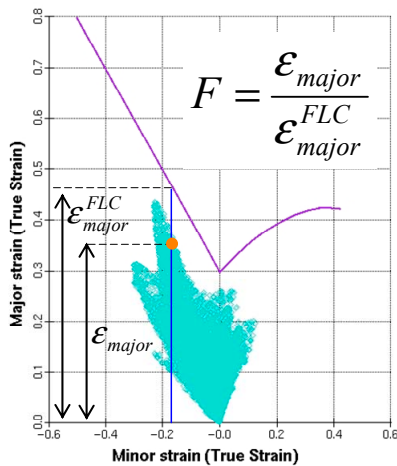


Figure 4. Definition of Failure Factor

The Maximum Failure Factor (MFF) is simply defined as the maximum value of Failure Factors for the entire part. It is an evaluation of the likely feasibility of the stamping process. The design objective is therefore to optimize drawbead strengths to achieve smallest MFF value under material and process uncertainties.

BASLINE MODEL

The draw development presented in Fig. 2 was taken from production design. A careful examination revealed that some of the drawbead segments could be combined into single ones, while the strengths of some others had little influences overall and could be fixed at constant values. Consequently the drawbead variables are reduced from the original 16 to 11 as shown in Fig. 5. It is used as the base model for the current investigation.

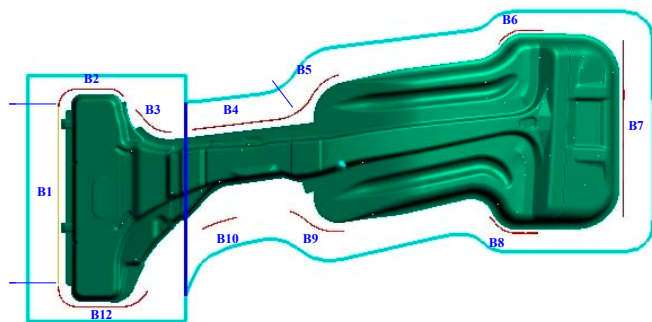


Figure 5. Baseline Model for the Study.

The commercial stamping software AutoForm is used to generate formability results. Since the focus of this paper is on the development of robust optimization methodologies for stamping feasibility in general, the accuracy of formability simulations is of secondary concern. The method itself is independent of particular software used.

The baseline values for drawbead strengths are listed in Table 2. The DBRF factor is a normalized value of its nominal strength used to facilitate the optimization process, and it will be used throughout the paper. It should be noted that the normalizations are based on the steel grade flowing into each drawbead, and therefore are not the same for different steel grades across the blank weldline. The Maximum Failure Factor for the baseline model is calculated to be 0.912.

Table 2. Baseline Drawbead Strengths

Drawbead	Drawbead Restraining Force	
	Factor	Nominal (N/mm)
B1	0.55	171.80
B2	0.45	140.50
B3	0.38	118.70
B4	0.20	271.90
B5	0.45	611.80
B6	0.60	815.80
B7	0.28	380.70
B8	0.56	761.40
B9	0.45	611.80
B10	0.15	203.90
B12	0.45	140.50
MFF	0.912	

DESIGN OPTIMIZATION

In this section, we will attempt to establish methodologies for design optimization in the absence of uncertainties. The design variables are drawbead strengths, and the target is to minimize the maximum Failure Factor (MFF). At first it appears that there are several well-established processes and they should be readily applicable to stamping optimization. However as it turns out, which will become apparent later in the paper, the complexity of stamping process poses its unique challenges.

SINGLE-OBJECTIVE OPTIMIZATION

Following standard optimization procedure, we first conduct a series of Design-of-Experiment (DOE) analysis with which a response surface will be constructed. The Optimal Latin Hypercube Sampling (OLHS) method [16] is adopted for DOE samples, and the ranges of 11 DBRF values are set to be +/- 50% of their base values. A total of 56 DOE cases are generated in the design optimization software iSIGHT-FD using the OLHS technique. Stamping analysis is then conducted for each DOE case using AutoForm – Incremental, which computes the Maximum Failure Factor (MFF) for each case.