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Stretching the limits of forming processes by robust optimization: A numerical and experimental demonstrator

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ABSTRACT

Robust design of forming processes is gaining attention throughout the industry. Many numerical robust optimization approaches have been proposed in literature and applied to a range of metal forming applications, often making use of a metamodel-based approach. However, published research is confined to numerical studies only. Experimental validation of the numerically predicted and improved process robustness is lacking. In this work, a deterministic and a robust optimization study is performed considering a stretch-drawing process of a hemispherical cup, covering both numerical work and experimental validation. For the robust optimization study, both the effect of material property scatter and process scatter are taken into account. For quantifying the material scatter that can be encountered in a production environment, samples from 37 coils of a drawing quality forming steel DX54D+Z (EN 10327:2004) from multiple casts have been collected. The numerically determined deterministic and robust optimum is subsequently validated by 2 sets of experiments using the collective of materials. The predicted difference in robustness between both optima, and the improved robustness of the robust optimum is also observed in the experiments. This demonstrates how robust optimization can assist in further stretching the limits of forming processes, while remaining robust with respect to sources of variation.

1. Introduction

In the design of sheet metal forming processes, a general goal is to achieve a lightweight and efficient design by making optimal use of the process and material capabilities. For this optimization question, finite element (FE) simulations are often used by coupling with metamodels and an optimization algorithm for efficient approximate optimization. An overview of metamodeling applications in structural optimization can be found in Simpson et al. (2008). Using these cheap surrogates, optimization can be performed more efficiently by reducing the number of required computationally expensive FE simulations.

However, deterministically optimized processes may become critical with respect to unavoidable sources of scatter in practice leading to product failures. This can be prevented by employing robust optimization techniques to incorporate input scatter and to quantify the resulting output scatter. The ultimate aim of a robust optimization study is the prediction and reduction of process scrap rate. For this purpose, an accurate prediction of the response scatter is needed that additionally corresponds to what is observed in practice.

Several applications of the metamodel approach in robust optimization of metal forming processes can be found in literature. All these approaches enable finding an optimal robust process design using FE simulations. Bonte (2007) proposed a metamodel-based robust optimization procedure and applied it to a deep drawing process of a small cylindrical cup product. The shape accuracy of the cup product and the process robustness was improved, which was numerically confirmed by performing a Monte Carlo analysis using FE simulations in the optimum. In Wiebenga et al. (2014b), a robust optimization study of a stretch-drawing process of a hemispherical cup is performed. Using a metamodel-based strategy, a deterministic and robust optimum is found after which the improvement in robustnes is demonstrated numerically for the latter optimum. The same application will be considered in this article, but with a revised optimization formulation, and including experimental validation of the numerical results. In Tang and Chen (2009) and Hou et al. (2010), robust optimization of a deep drawing process

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is performed considering a square cup and an automotive part respectively. In both publications, a numerical comparison is made between the robust and deterministic optimum in terms of the objective function value, which numerically proved the increased robustness for both processes. In Sun et al. (2010), a draw bead design was optimized in a robust manner to prevent wrinkling and fracture of a deep drawing process of an automotive part. The resulting robust optimum was validated using a single experiment, resulting in a satisfactory deterministic product showing no wrinkling or fracture.

Published research on robust optimization of forming processes using a metamodel-based strategy is mainly confined to numerical studies only. Experimental validation of the numerically predicted and improved process robustness is lacking in the literature. This is because validation of process robustness requires performing many experiments to capture even the most pronounced sources of variation. However, only by supporting the numerical results with experimental outcomes is one able to determine whether the numerically predicted robust optimum is, indeed, more robust compared to the deterministic optimum and is as robust as in simulations. For this purpose, the difference in the number of product rejects between both optima needs to be determined experimentally.

In this work, a metal forming process is optimized in both a deterministic and a robust way, and experimental validation of the process robustness in both optima is performed. The results demonstrate how robust optimization can assist in further stretching the limits of forming processes while remaining robust with respect to sources of variation.

The considered forming process, numerical model and the optimization problems will be introduced in Section 2. Next, the main sources of variation in the forming process are introduced and quantified in Section 3. The results of both optimization studies are subsequently presented in Section 4. The numerically determined optima are validated by 2 sets of experiments. The experimental procedure and results are described in Section 5 and the difference in robustness between the deterministic and robust optimum is discussed. Moreover, a comparison between the results of the numerical and experimental robustness analyses is made. A discussion is provided in Section 6. Finally, Section 7 will present the conclusions of this work.

2. Application to a stretch-drawing process

A deterministic and a robust optimization study are performed considering the stretch-drawing process of a hemispherical cup. For this purpose, an objective function and constraints must be formulated. Solving an optimization problem can be defined as finding the values of the design variables which minimize the objective function subject to constraints. In case of robust optimization, additional noise variables are taken into account in the optimization study.

An impression of the considered stretch-drawing process is given in Fig. 1. The stretch-drawing process and numerical model are described in Section 2.1 and Section 2.2 respectively. The deterministic and robust optimization problem are introduced in Section 2.3. Before proceeding with the optimization studies, the outcomes of the FE model are experimentally validated and described in Section 2.4.

2.1. Experimental procedure

An impression of a hemispherical cup resulting from the stretch-drawing process is given in Fig. 2a. The hemispherical cups are formed from circular blanks with a nominal thickness of 0.79 mm. A drawing quality forming steel is used, i.e. DX54D+Z (EN 10327:2004). This material, a low carbon continuously annealed hot dipped galvanized steel with EDT surface finish, is chosen because of its wide application in cold forming processes in the automotive industry.

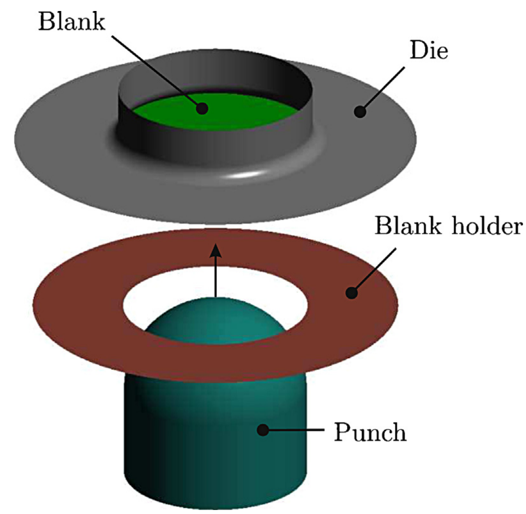

Fig. 1. Impression of the considered stretch-drawing process.

The experiments are performed using an Erichsen universal sheet metal testing machine. To control the process, both the blank size and the Blank Holder Force (BHF) are defined as design variables in this work. The blank radius (r) can vary between 80 mm and 90 mm whereas the BHF (F) can vary between 1 kN and 30 kN. Tooling with a punch diameter of 67 mm, a die opening diameter of 77.4 mm and a die shoulder radius of 8.5 mm is used. The blanks are lubricated using Zeller & Gmelin PL61 Multidraw oil. The amount of lubricant applied is 1.5 g/m^2. The blanks are formed by combined stretching and drawing using a prescribed punch displacement at a velocity of 1 mm/s. The optimal combination between stretching and drawing that results in the optimal product quality is unknown *a priori*. Determining the optimal combination resembles a non-trivial optimization problem commonly encountered in the design of forming processes.

2.2. Numerical model

The FE simulations of the stretch-drawing process are performed using the FE code DiekA (2013). Due to symmetry of the product and material properties, only a quarter of the product is modeled, see Fig. 2b. The blank is discretized using triangular discrete Kirchhoff shell elements with 5 integration points through thickness. The element size for the blanks with varying blank radii is kept constant at 1.0 mm. An average friction coefficient of 0.18 is utilized. The Vegter yield locus model is used as described in Vegter and van den Boogaard (2006), combined with the Bergström–van Liempt hardening relation as described in van Liempt (1994). The material parameters for the yield locus model and hardening relation are provided in Appendix A. The procedure for efficiently obtaining these parameters is described in Section 3.

2.3. The optimization problem

The objective of the optimization problem is to maximize the product height (h) while preventing wrinkling and local thinning of the product and requiring a minimal remaining flange width. The product height is used as an optimization objective in this work although generally, the product height is defined by the final required product geometry. However, by doing so, an optimum is obtained which is critical with respect to wrinkling, local thinning