PARAMETER DESIGN FOR SHEET METAL HYDROFORMING PROCESSES

U. Gather[2], W. Homberg[1], M. Kleiner[1], Ch. Klimmek[1], S. Kuhnt[2]
[1]Chair of Forming Technology, University of Dortmund, Germany; [2]Chair of Mathematical Statistics and Industrial Applications, University of Dortmund, Germany

Summary

This paper presents results of a cooperative research programme on the development of new offline process design methods for sheet metal hydroforming processes. Fundamental investigations regarding the influence of process parameters and their interplay are discussed. Parameters are to be chosen such that the high-pressure sheet metal forming process is optimised with respect to multiple quality characteristics (multi-response) i.e. blank thinning and geometrical accuracy. It is essential to these investigations to consider geometrical features within the tool design as process parameters. The data ascertainment is carried out by applying the finite element method. Multiple process variation and optimisation strategies will be modelled according to the principles of the statistical design of experiments (DOE).

Keywords: Sheet metal hydroforming, Offline process optimisation, Design of experiments

1 Introduction

The process of high-pressure sheet metal forming (HBU), developed at the Chair of Forming Technology (LFU), University of Dortmund, offers several technological advantages for example higher deep drawing ratios, better geometrical accuracy and cost efficiency compared to conventional deep drawing processes. Additionally this technology is more suitable for deep drawing modern high strength steel or aluminium alloys which are utilized more and more in the automotive industry [1,2,3,4].

Robust parameter design in the sense of Taguchi is a widely recognized method for improving the quality of products of manufacturing processes. This is mainly achieved by making the output response insensitive to difficult-to-control variation while at the same time keeping it on target. Most research in robust process design focuses so far on problems with a single response [5,6]. Practical problems however, often require the simultaneous optimisation of many quality characteristics. This is the case in sheet metal forming processes, where increasing demands on quality in connection with environmental constraints are forcing manufacturers to constantly improve their manufacturing processes. Here conventional processes often encounter technological limits.

For the integral understanding of the complex high-pressure sheet metal forming process and the study of the parameters' interactions new analysis methods for offline process design are required. These new methods will allow a more efficient and faster tool design and optimisation especially for free form shaped geometries. Fundamental investigations are to be carried out in order to identify, classify and choose proper levels of significant process parameters with respect to multiple quality characteristics (multi-response) in tool geometries with sculptured surfaces. It is essential to these investigations to consider geometrical features within the tool design as dominant process parameters affecting the forming process severely. These studies are carried out by simulating the forming process with the finite element method. Data evaluation and the search for optimal design parameter values are carried out by statistical methods, based on experiments following statistical design of experiments (DOE). The complexity of the analysed geometries has been increased steadily ever since. Some results of these works are discussed in the following.

2 Virtual modelling and design of experiments (DOE)

The geometrical complexity of the considered model has been kept low for primary investigations. Thereby results gained by statistical analysis can be evaluated using the existing long term experience in high-pressure sheet metal forming processes. For this purpose the forming operation of a stripe made of a mild steel alloy (DC 04) as a segment of a virtual rail was developed, **Figure 1**. The rail is designed in form of a step in order to obtain specific information about the forming characteristics. The radii vary from 3 mm to 5 mm which will be formed differently by the same pressure of the working media. The increase of depth from 18 mm to 48 mm will cause an inhomogeneous strain distribution within the rail. Due to the asymmetric design a non-uniform material flow is expected in the flange area of the blank.

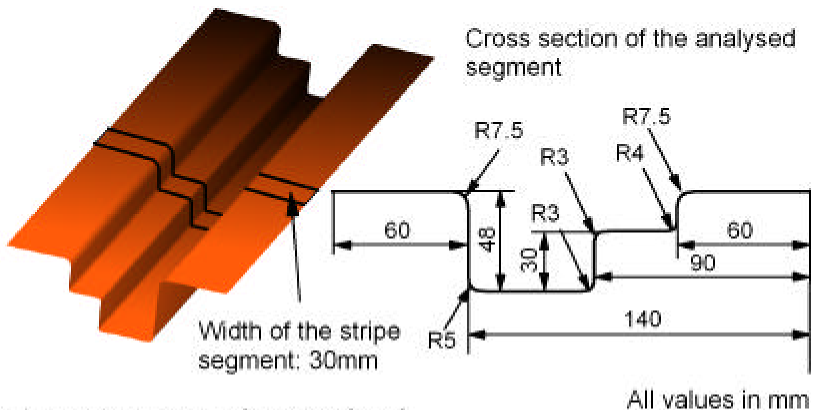

Figure 1: *Design of a virtual rail*

In order to gain the outmost information out of this model it is useful to focus on the blank holder force and the pressure of the working media as most important controllable design parameters. Disturbances on the process can be expected from different friction coefficients between the contact counterparts and from fluctuations in the thickness of the blank sheet, which present an uncontrollable (noise) parameter. FE-simulations are conducted following a product array plan in the sense of Taguchi: settings for the pressure of the working media and the blankholder force given by a central composite plan are repeated for each setting of a 2^2-factorial plan for the friction coefficients and the blank sheet thickness [6,7].

For every experiment the result is described by two quality characteristics in order to be analysed by statistical methods, which are to be optimised simultaneously. They describe the form and geometric accuracy as well as the thinning of the blank sheet caused by the forming operation. The term of form and geometrical accuracy needs a precise definition in this case for it cannot be compared with its original meaning. Normally the form and geometrical accuracy is defined as the deviation between the produced part and the constraints prescribed by the part design. The measured values have to be within given tolerance limits. Here the definition of this quality characteristic is somewhat different, because there is only a virtual model which cannot directly be compared with a real structure. Therefore it is best to regard the outline of the die as the optimum to be fitted. The area between the formed blank and the die can be seen as a value, quantifying a loss of quality. **Figure 2** shows the described area. The thinning of the blank sheet can be regarded as a method to obtain a second value, giving further information on the forming result.

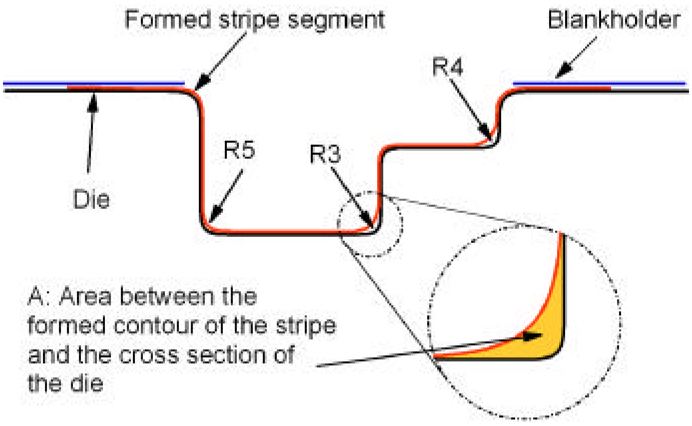

Figure 2: *Form and geometric accuracy*

The goal should be not to exceed a specific value for thinning, for then cracks will occur. An upper limit for the blank thinning is set at 20%. On the other hand a uniform thinning throughout the body with a minimum value of 5% is appropriate in order to improve the mechanical properties induced by material work hardening. The data resulting from the experiments are analysed by the method described in [8], giving the joint optimisation

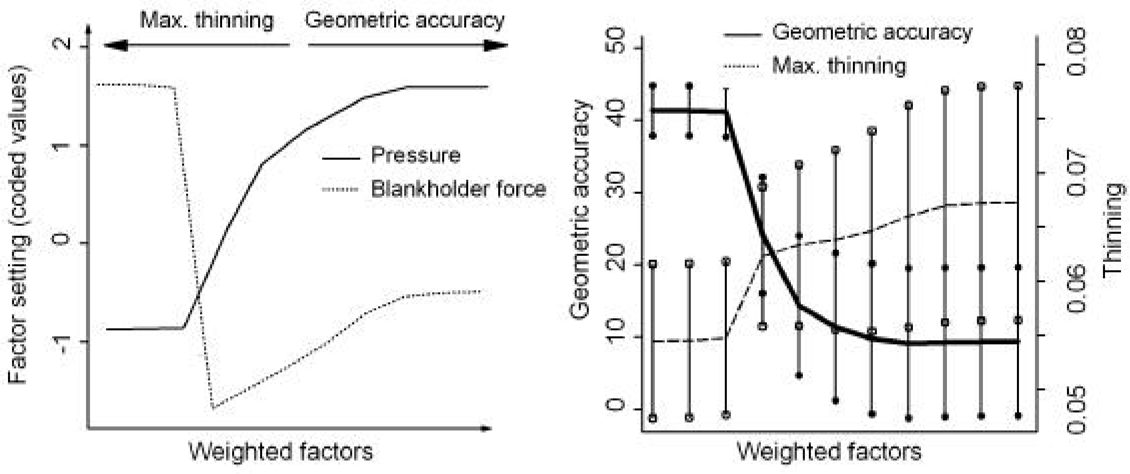

Figure 3: *Statistical evaluation for optimal factor settings*

plot of **Figure 3** as a result. Prediction models for the mean and variance of the quality characteristics are estimated and plugged into a risk function. The considered risk function theoretically becomes zero if the process is always on target, meaning that the means of all quality characteristics equal the target values and the variances are zero. The considered risk functions depend on a pre-specified weighting of the quality characteristics, describing the importance of reaching an optimal result for each characteristic. For different possible weightings values of the controllable design parameter are determined which minimize the estimated risk function. On the left side of **Figure 3** these values are plotted against possible weightings. The right side shows the corresponding predicted means and variances of the characteristic geometrical accuracy and thinning.

The evaluation of the statistical data points of the pressure of the working media and the blankholder force have a significant influence on the forming result. The effects on the quality characteristics are contradictory. A better geometrical accuracy simultaneously evokes a higher thinning of the blank sheet. This is evident, because a better geometrical accuracy can be achieved with a higher pressure of the working media, which creates a greater stretching of the blank sheet. The optimum settings have to be chosen according to a compromise between geometrical accuracy and thinning of the blank sheet.

3 Extension to design parameters controlling geometrical features

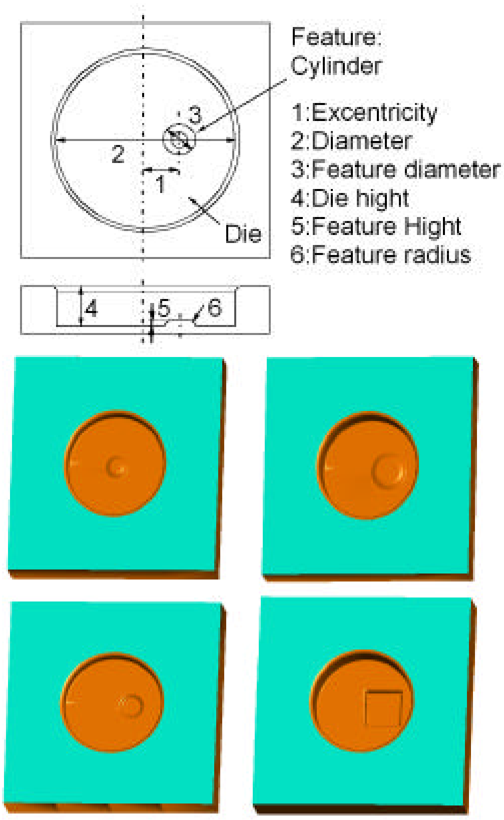

Figure 4: Geometric feature variations

In the development stage of a sheet metal hydroforming process the geometry of the workpiece itself can quite often still be slightly changed. To study the effect of geometrical features on the quality of the hydroforming result a modular assembly model is developed, which combines different basic geometrical features i.e. geometrical dimensions, position and shape. Some examples of the geometrical variation are illustrated in **Figure 4**. For this purpose basically a die is designed as a tool which can be combined with different geometrical features i.e. cylindrical and square hutches or pockets. These geometries vary in their dimension and position, see **Figure 4**. Combined with the process parameters a sum of 10 parameters have to be varied within certain margins. Several investigations have been carried out in order to determine the sensible margins for the parameter settings, see **Table 1**. For different basic geometries screening experiments have been carried out to identify those of the 10 parameters, which have distinguished effects on the quality characteristics. The quality characteristic are the geometrical accuracy and the thinning. So called Plackett-Burman designs [9] are used which allow the investigation of many parameters using very few experiments. With 10 parameters only 12 experiments are necessary. For all parameters six experiments on a high level (+) and six experiment on a low level (-) are included.

***Table 1**: Design parameter levels*

	Variable	Levels - / +
Noise parameter	Friction coefficient *(m)*	0.065 /0.075
	Thickness of original blank sheet *(s)*	0.9 /1.1 mm
Process parameter	Blankholder force (F_{BH})	20 / 35 kN
	Pressure of the working media *(p)*	60 / 100 MPa
Geometrical parameter	See **Figure 4**	

It is assumed, however, that the main effects of important parameters are much larger than effects due to interactions between two or more parameters. An effect describes the change in process performance associated with going from low (-) to high level (+) settings. Using a Plackett-Burman design [9] the main effect of each parameter can be estimated by the difference between the average of the quality characteristic measurements made at the high level of the factor and the average of the measurements made at the low level. In **Figure 5** experimental results for the case of a quadratic feature within a circular die are summarised. In these main effect plots the values of the quality characteristics are plotted for each parameter. Additionally the average points of the low and high level measurements are indicated and connected by a line. The higher the slope of the line the higher the effect of the parameter on the quality characteristic.

Figure 5 shows that the thickness of the original blank sheet, the feature radius, the blankholder force and the height of the feature have the highest effect with respect to the geometrical accuracy. Concerning the maximal thinning the height of the feature plays a dominant role. All experiments with a height of 40 mm lead to cracks. It seems advisable to change the region-of-interest of the parameter feature height in further experiments. Next to the feature height, the thickness of the original blank sheet, the feature radius and die height are the most important parameters.

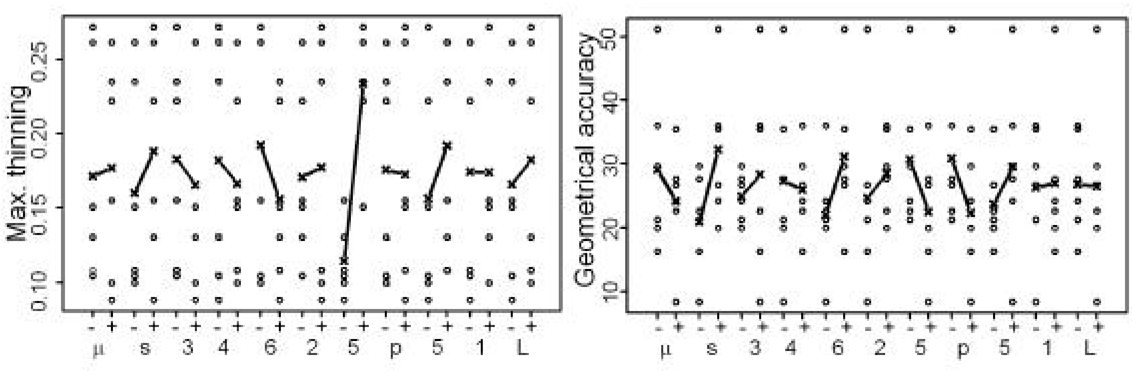

***Figure 5:** Main effect diagramme for two quality characteristics*

4 Outlook

The identification of the most important parameters for modular assembly models makes it feasible to conduct more refined optimisation experiments. These will lead to statistical models usable to predict response functions, as done in paragraph 3 for the simpler model. The results of screening experiments for the modular assembly models will not only be used to compare the process performance due to geometrical parameters for specific geometries of the die and feature but also across such geometries. The geometrical complexity will be increased steadily in order to get detailed information about the effect of geometrical features on the quality characteristics and continue to free form shapes.

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