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Assessment of sensitivity of numerical simulation in sheet metal forming process applied for robust design

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Abstract. Considering variation of influent factors is a critical issue to enhance the robustness of sheet metal forming process in the product design process. The stochastic variability of uncontrollable factors results in the variations on the formed part which can lead to rejected parts. Since the inherent sources of variation in the sheet metal forming process comes from part-to-part, within batch and batch-to-batch variation. Therefore, the prediction and control of the variability influencing on the performance of the product is an essential demand of automotive and aeronautic manufacturers. Moreover, it is very necessary to have a numerically dedicated tool which predicts the process variability with a good confidence. In this paper, prediction of the variations of the formed part due to the variabilities of the sheet stamping process and the workpiece by numerical simulation will be carried out.

Keywords: robust design, variability, sheet metal forming, sensitivity analysis

1 Introduction

Stamping process is an effective process applied for fabricating body panels in automotive manufacturers. The fact that there are around 100 to 150 stamped metal panels on vehicles produced nowadays. The process is mainly used in production of large batch because designing and manufacturing the stamping tools are very expensive and time-consuming [1]. Hence, reduction of time in the tooling design phase as well as elimination of expensive physical experiments is considered as objectives which the manufacturers would like to obtain. As a solution for this issue, FEA software has been a rapid and effective tool for design and verification of new product propositions in automotive industries in the last few years. Nevertheless, quality of produced parts is one of the most important issues which need to take into account to satisfy customer's specifications. The stamped parts must respect functional, geometrical aesthetic requirements. Thereby, enhancement of reliability of the design by using numerical simulation is a focus of this research work.

In industrial practice, the industrial actors often cope with several defects occurred on the stamped parts in which shape defects due to springback, thinning and wrinkling are principal problems. The sources provoking these defects are from input parameters' variations of the forming process. The variation sources of draw bending process are synthesized in Figure 1.

As a consequence, the variabilities result in poor product quality. In order to enhance the robustness of the sheet metal forming processes or in other words, to minimize the reject rate, the fluctuations must be taken into account in the part and tools design stage.

As mentioned above, the FEM numerical simulation is the solution for shortening the lead-time and saving the cost for the experiments in the sheet metal forming process. Presently, the FEM software can evaluate any virtual forming process with an acceptable accuracy. However, there is still difference between results from numerical simulations and results from physical experiments. The cause of the difference may be due to inconsistent FE models or incorrect inputs parameters or deviation of the input variables [3]. In other words, although the geometry and the material properties of the tools and the sheet blank are fixed, the variations in the method of FE modeling by users may lead to various results [2].

Previously, there were several research works which investigated the effects of numerical factors such as the element size of sheet trip, the hardening law, the precision of modeling tool radii and the dynamic effect on the springback results of the U-draw bending benchmark problem [4]. He and Wagoner [5] investigated the impact of the finite element mesh system of the blank on springback results using the same benchmark problem. The effect of the dynamic term on springback was evaluated by Chung et al. [6]. Numerical factors affecting springback including contact damping parameter, penalty parameter, blank element size, number of corner elements were investigated by Lee and Yang, [2]. For the last few years, a couple of investigations in relation to the effectiveness of numerical models have been also taken into consideration making comparison between numerical predictions and experimental results [7]. Particularly, the influence of numerical parameters comprising the type of the utilized element, the number of integration points, the hardening rule and so forth, with the aim to improve the effectiveness and reliability of the numerical results.

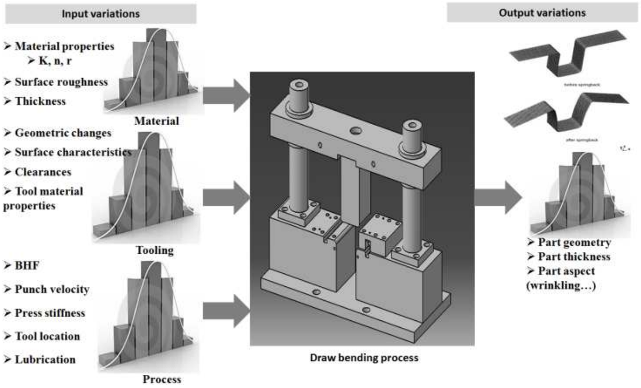

Fig. 1. Draw bending process and its variation sources

Xu et al. [8] analyzed the effect of sensitive factors in a U-bending process of Numisheet'93 benchmark problem using a fully explicit solution scheme in which the impact of integration points number, blank element size and punch velocity was researched.

It can be seen that all mentioned literatures concentrate on considering the effects of numerical parameters on the virtually formed parts, there were hardly any studies concerning evaluation of reliability of FEA software. In other words, qualifying the sensitive level of numerical simulation tools with very small variations of the scattering parameters in the sheet metal forming process is crucial to enhance the robustness of digital programs in the prediction of variability of the process. Since very small variability of the sheet's material properties, the blank thickness and tooling parameters influence on finished part, particularly, springback variation in sheet metal forming process.

Therefore, the purpose of this research work is to focus on evaluation of prediction capability of the stamped part's variation derived from the input parameters' variability using commercial FEA software.

In general, in this study, the objective is to analyze the reliability of FE numerical simulation tool, namely ABAQUS software, when having very small variability of input parameters, so then whether output results, particularly springback variations, are sensitive with the variability or not. Meaning that the software can be sensitive to how small percent of variability is. In the following sections, problem modeling will be presented in which a case study, springback measurements and numerical modeling and simulation will be discussed in Section 2. In section 3, investigation of reliability of numerical simulation will be presented. Evaluation of sensitivity of numerical simulation will be shown in Section 4. The last section is conclusion.

2 Problem modeling

2.1 Case study

The U-shaped part, a benchmark problem of NUMISHEET'93 International Conference [10], is investigated in this paper. However, the part's geometrical dimensions are modified according to industrial requirements and the part is named open-channel part. This part is a representative product commonly used in automotive industry to reinforce for body panel or base. A schematic view of die, punch, blank and their dimensions for the draw bending process is shown in Fig. 2 which is used in this study. Table 1 shows dimensions for the draw bending process.

Table 1. Dimensions for the draw bending process

Parameters	W1	W2	W3	W4	R1	R2	G1	Stroke
Dimensions (mm)	57.7	60	150	150	5	10	1.15	60

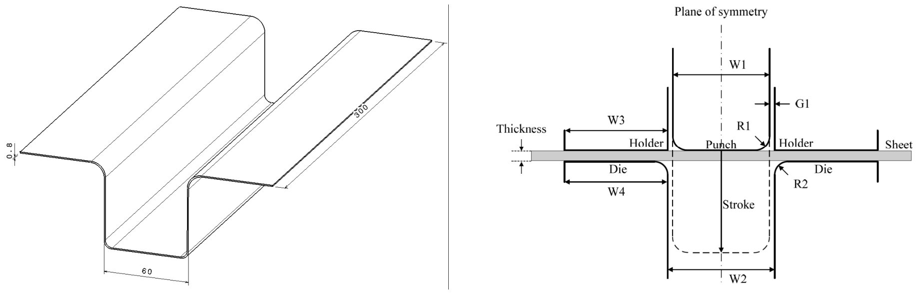

Fig. 2. A schematic view of tools and dimensions for the open-channel part

The simulation work in this study is carried out based on the experimental results of Ledoux et al. [1]. The blank is obtained from rolled sheet of 0.8 mm thick, 300 mm long and 300 mm width. The accuracy of the length and width dimensions of the blank is 0.5 mm. The blank holder force of 90 KN is applied in this case. Blank material is DC04 steel with the material properties presented in Table 2.

Table 2. Blank's material properties [1]

DC04 material	
Young's modulus	206.62 GPa
Yield strength	175 MPa
Poisson's ratio	0.298
Lankford's coefficient	$r_{0^\circ} = 2.09$
	$r_{45^\circ} = 1.56$
	$r_{90^\circ} = 2.72$
Density	7200 kg/m^3
Strain hardening's coefficient	K = 466 MPa
	n = 0.2056

Moreover, experimental measurements prove that part profiles remain symmetric. Therefore, simulation of numerical experiment will be performed on half of the profile.

2.2 Springback measurements

In order to characterize the total springback distortion, three measurements including the springback of wall opening angle (β_1), the springback of flange angle (β_2) and sidewall curl radius (ρ) are shown in Fig. 3. They describe the variation of the part's cross-sectional shape obtained before and after removing the tools. For calculating the springback measurements, it is necessary to determine the measurements before and after springback. To do so, the least square method is applied to identify the points of A^0, B^0, C^0, D^0 and E^0 on the formed part's profile according to given x and y coordinates.

Based on the known point coordinates, the wall angle (θ_1^0) and the flange angle (θ_2^0) before springback are computed. Similarly, other points of A, B, C, D and E are defined on the part's profile which the tools have been removed.

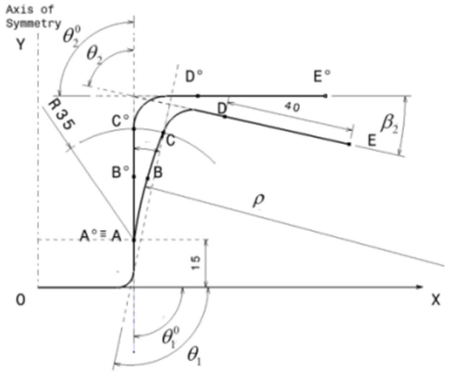

Fig. 3. Schematic view of springback profile and parameters

They are then used to calculate the wall angle (θ1) and the flange angle (θ2) after springback. The side wall curl radius is estimated by a curve fitting technique through three points A, B and C to construct a circular arc.

2.3 Numerical modeling and simulation

To predict the springback variations derived from the variability of input parameters, numerical simulation is an efficient solution. The FE simulation of the 3D draw bending process of the open-channel part is carried out by the ABAQUS/CAE 6.11-2. The problem is modeled according to the schema of Fig. 2 and the process parameters and tools configuration are applied as in Table 1. The key characteristics of numerical simulation are shown in Table 3.

Table 3. The key characteristics of numerical simulation

Blank	
Element type	Shell S4R
Number of elements	5340
Integration points	7
Yield function/Plastic potential	Hill48 [9]
Hardening rule	Isotropic, Swift model $\sigma = K(\varepsilon_0 + \varepsilon)^n$
Tools	
Tool type	Analytical rigid surface
General aspect of the code	
3-D draw bending	Dynamic, Explicit
Springback	Static, General
Friction coefficient: 0.15	

As mentioned above, the half of problem is modeled. Hence, boundary conditions and symmetric condition are applied on the half part of the model.

3 Investigation of the reliability of numerical simulation

With the purpose of investigation of sensitive level of numerical simulation software so that a global approach is proposed and illustrated as Figure 4 in which input parameters are run by using method of Design of Experiments (DOE) to make variations, and then, the variation of input parameters are used as input parameters of numerical simulation. As a result, the simulated part will be calculated in the Matlab to define the responses. In this study, only part-to-part variation is considered, namely the blank thickness variation is regarded as an input variable of this investigation.

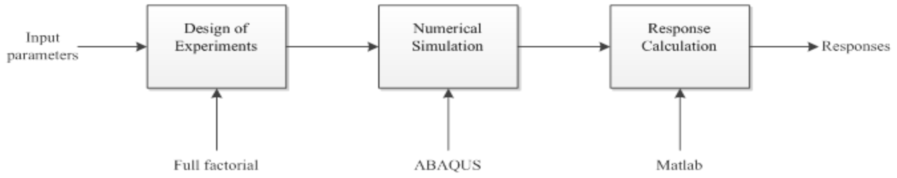

Fig. 4. The globally proposed approach in evaluation of sensitivity of numerical simulation

In particular, the investigated model is demonstrated in Figure 5. Starting from the nominal input parameters of the material, tooling and process as Section 2, numerical simulation of the draw bending process of the open-channel part is run in the ABAQUS/CAE 6.11-2 in which the part shape is performed in two steps of forming and springback step.

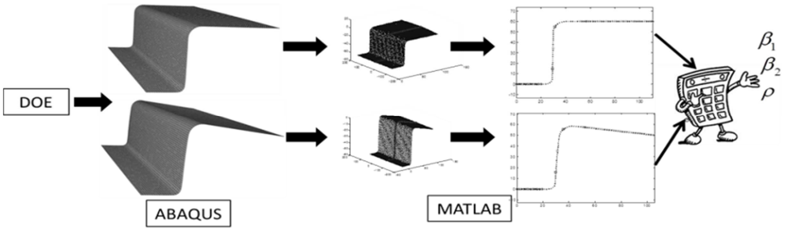

Fig. 5. The investigated model of reliability of numerical simulation

Consequently, nodal coordinates of deformed part are extracted from the ABAQUS. Afterwards, they are used to compute the springback parameters of β_1, β_2, and ρ in the Matlab. After calculation, the results of the part's measurements before and after springback are listed in Table 4.

Table 4. The part's measurements before and after springback

	Before springback		After springback		Springback measurements		
Measurements	θ_1^0	θ_2^0	θ_1	θ_2	β_1	β_2	ρ (mm)
Results	90.5°	90.5°	97.59°	84.93°	7.096°	5.561°	236

A comparison between the numerical simulation result and the experimental result implemented by Ledoux et al. [1], the numerical result is very close to the experimental one. The deviation between experimental and numerical results is less than 1 mm which shows good prediction by FE numerical simulation.

To calculate automatically, the design of experiments, numerical simulation and response calculation are coupled in the workflow of ModeFRONTIER™. The workflow in the ModeFRONTIER™ is presented in Figure 6.

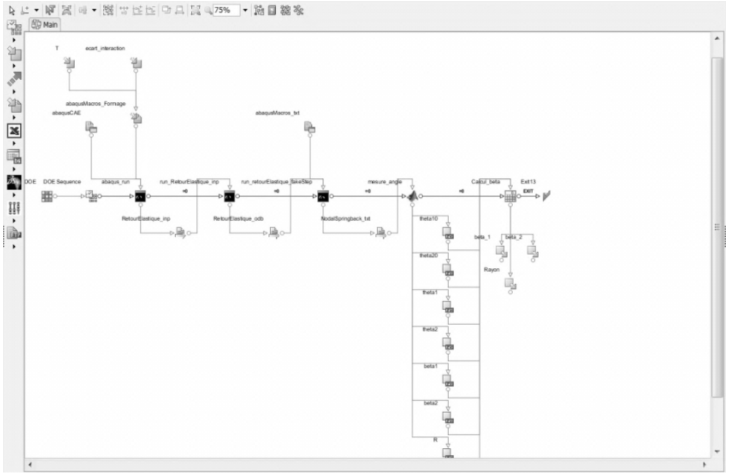

Fig. 6. The workflow of the proposed approach

4 Evaluation of sensitivity of numerical simulation

Sensitivity function is used to evaluate the reliability of the numerical simulation software as below:

- Smaller and bigger value:

$$\alpha = \frac{\partial f}{\partial x}(x_0) = \frac{f(x_0+\Delta_e)-f(x_0-\Delta_e)}{2\Delta_e} \tag{1}$$

- Smaller and nominal value:

$$\alpha = \frac{\partial f}{\partial x}(x_0) = \frac{f(x_0)-f(x_0-\Delta_e)}{\Delta_e} \tag{2}$$

- Nominal and bigger value:

$$\alpha = \frac{\partial f}{\partial x}(x_0) = \frac{f(x_0+\Delta_e)-f(x_0)}{\Delta_e} \tag{3}$$

Where, x_0 corresponds to nominal thickness and Δ_e is variation range between thickness values.

Thickness variation parameters and sensitivity values are shown in Table 5. In particular, the variation is expressed through gradual decrease of variation percent of nominal thickness. It is assumed that the thickness in the whole part is constant. The other parameters of the process are fixed with nominal values. Numerical modeling and simulation of the process still remains as mentioned in Section 2. Output parameters are springback measurements of β_1, β_2 and ρ.

Sensitivity analysis results are shown Figure 7. Observation from sensitivity analysis graphs shows that the sensitivity of numerical simulation software in this case can reach for level of blank thickness variation of 5 % of nominal thickness. It can be seen that three sensitive lines of three springback responses converge at the point of 5% of nominal thickness. Due to the fact that the smaller the variation range, the more closed three sensitive lines are.

Table 5. Thickness variation parameters and sensitivity values

Variation (%)	Δe (mm)	Thickness variation (mm)	α(β1) (°/mm)	α(β2) (°/mm)	α(ρ) (mm/mm)
20	0.16	0.64	14.4212	11.3241	-359.3706
		0.8	6.3059	5.1569	-65.7868
		0.96	-1.8094	-1.0104	227.7971
10	0.08	0.72	13.4137	4.4931	-263.4972
		0.8	4.9432	1.2885	33.5350
		0.88	-3.5273	-1.9161	330.5673
5	0.04	0.76	13.8783	1.7104	-92.5804
		0.8	6.9821	2.4945	49.0883
		0.84	0.0859	3.2787	190.7571
2	0.016	0.784	38.6269	4.7084	-284.1957
		0.8	21.9402	5.1717	-67.8929
		0.816	5.2534	5.6349	148.4098
1.5	0.012	0.788	1.2409	-2.5120	115.8318
		0.8	-2.8300	0.2649	126.1214
		0.812	-6.9010	3.0419	136.4111
1	0.008	0.792	4.5147	-9.6161	353.8053
		0.8	-1.9217	-1.9243	287.6912
		0.808	-8.3580	5.7675	221.5770
0.8	0.0064	0.7936	21.0978	9.4679	-848.9659
		0.8	4.1734	9.6291	-433.2124
		0.8064	-12.7511	9.7903	-17.4588
0.5	0.004	0.796	170.8839	42.9871	-2025.5843
		0.8	83.1412	32.0626	-902.5713
		0.804	-4.6014	21.1382	220.4417
0.2	0.0016	0.7984	62.9189	-53.2250	462.2954
		0.8	-136.9051	-38.8243	1393.4893
		0.8016	-336.7291	-24.4236	2324.6832
0.1	0.0008	0.7992	-33.7328	-81.3877	4490.6412
		0.8	-90.2131	24.8825	2733.6190
		0.8008	-146.6935	131.1527	976.5967
0.05	0.0004	0.7996	1453.4986	202.5773	-5962.3799
		0.8	692.7517	174.3740	-5902.7587
		0.8004	-67.9952	146.1708	-5843.1374
0.01	0.00008	0.79992	2023.2555	278.3391	-16901.7565
		0.8	-2675.0272	11.9680	14256.7433
		0.80008	-7373.3098	-254.4031	45415.2431

5 Conclusion

Numerical modeling and simulation of U-shaped draw bending process has been carried out to show the effect of blank thickness variation on the variability of output

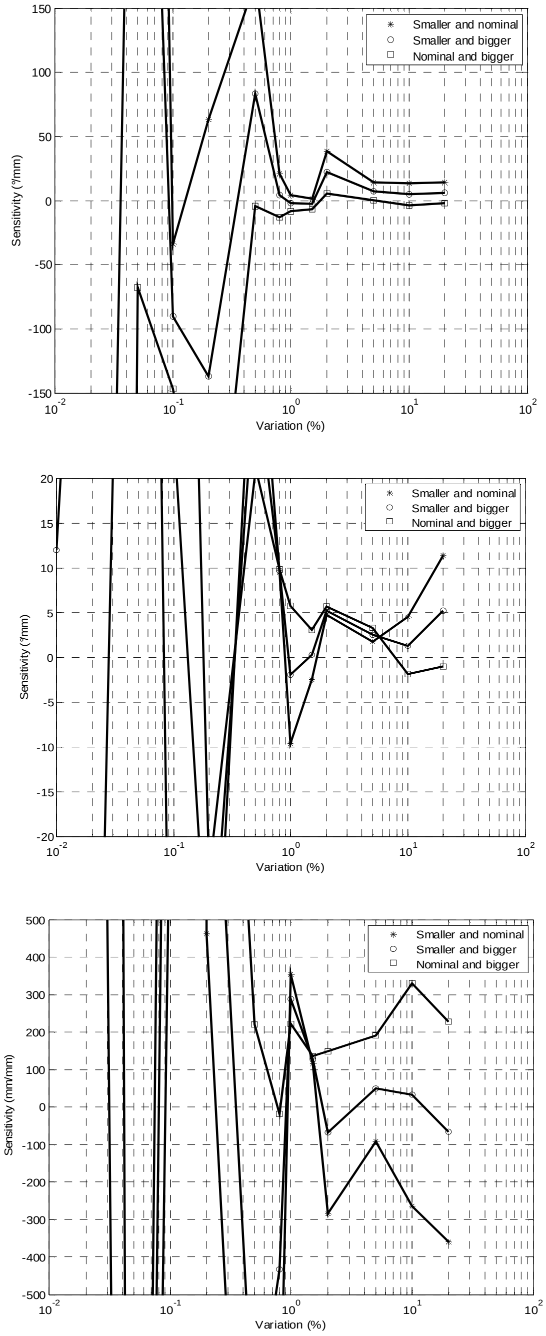

Fig. 7. Sensitivity of numerical simulation α(β1), α(β2), α(ρ) respectively with thickness variation

response of springback.

Additionally, the paper has been investigated the sensitivity of numerical simulation software, namely ABAQUS, in modeling and simulating the U-shaped draw bending process. The result has shown that the reliability of the software can reach for level of blank thickness variation of 5 % of nominal thickness in this case study. The sensitivity evaluation is built and calculated automatically in the ModeFRONTIER™. The proposed approach has been developing which provides a tool in taking into account the variation of input parameters affecting on output responses in the sheet metal forming process by using FEM contributing to improvement robust parameter design methodology.

This project is being in the research process. Construction of metamodels based on approximating surface response to predict variation of other factors will be employed in the next works.

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