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PREDICTING THE EFFECTS OF MATERIAL AND PROCESS PARAMETERS ON SPRINGBACK BY FEM NUMERICAL SIMULATION IN SHEET METAL FORMING

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ABSTRACT: *The progress on FEM numerical simulation tools can increase the level of predictability and precision, but these tools remain dependent on the quality of experimental data defining the model parameters of materials and the process. Unfortunately, these experimental data always has inherent variabilities regarding process parameters, material properties and the sheet's dimensional variations. As a consequence, there are always discrepancies between results from physical tests and numerical simulation trials. Moreover, the sensitivity of finite element models of sheet metal forming simulation is not always sufficient to take into account the very small variations of input parameters. To answer these challenges, in this paper a novel approach to determine the minimum sensitivity threshold in numerical simulation of the sheet metal forming process is proposed. This method contributes importantly to the computer experiments when using Design of Experiments in executing uncertainty propagation. Moreover, the influence of process parameters on springback in sheet metal forming is predicted by sensitivity analysis.*

KEYWORDS: *sensitivity threshold, sensitivity analysis, sheet metal forming, FEM numerical simulation, variation.*

1 INTRODUCTION

The sheet metal stamping is a productive process which is mainly used in mass production, particularly to produce the components for "body in white" in the automotive industry. More specifically, there are around 100 to 150 stamped metal panels ranged from small to large and from simple to complex panels such as fenders, hoods and body sides, on vehicles produced nowadays such as automobiles, light trucks, and minivans [Majeske and Hammett, 2003]. Due to ever increasing competition, the cost reduction and productivity improvement are demands which the automotive manufacturers aim at. However, the sheet metal stamping design process is very expensive and time-consuming because of being heavily experience based and the costly trial-and-error loops [Tekkaya, 2000]. Indeed, an automotive plant needs to produce about 40-50 critical panels per a car model that require 150-200 stamping dies [Drishtikona, 2009]. Hence, it is very necessary to shorten the process design time and eliminate costly physical trials which add to the manufacturing cost. As a solution for this issue, CAD software and FEM-based numerical simulation tools have been

widely used to support in the design and product development process. A designer can use sheet metal stamping simulation to assess the possibility of successfully manufacturing a sheet metal stamping part without the expense of making a physical tool. Nevertheless, it still has the discrepancy between results from computer simulation and physical experiment. The discrepancy can be provoked by either inappropriate FEM models, incorrect input or a deviation of the input variables [Jansson et al., 2008].

Furthermore, searching a manufacturing process design producing the parts of which specifications are as close as possible to the nominal values is the goal in the design process [Ledoux et al., 2010]. Unfortunately, the automobile manufacturers often cope with several defects on the stamped parts in which shape defect due to springback, thinning, wrinkling and tearing are conspicuous defects in the sheet metal stamping process.

The variations in material properties, blank thickness, lubrication, tooling dimensions and process parameters can be causes of those variations in performance of the output. As a consequence, it leads to amplified variations and problems in the down-

stream assembly process, and in turn, results in quality issues. The sources of the inherent variations stems from the part-to-part, batch-to-batch, and within batch variation during production process [Majeske and Hammett, 2003]. Karthik et al investigated the coil-to-coil, laboratory-to-laboratory and test-to-test variability in the sheet material properties by measuring more than 45 coils of the same material independently at three laboratories. They found that the scatter laboratory-to-laboratory is approximately equal to test-to-test scatter at one laboratory. Coil-to-coil variations are typically greater than the observed test-to-test scatter, particularly in the transverse direction [Karthik et al., 2002]. The uncertainty and variation sources in the sheet metal stamping process are synthesized in Figure 1 [Nguyen et al., 2013]. Thus, taking the uncertainty and irreducible inherent variability into account as well as optimizing the process based on FE numerical simulation are major issues should be tackled to obtain a robust process design in the sheet metal stamping process design.

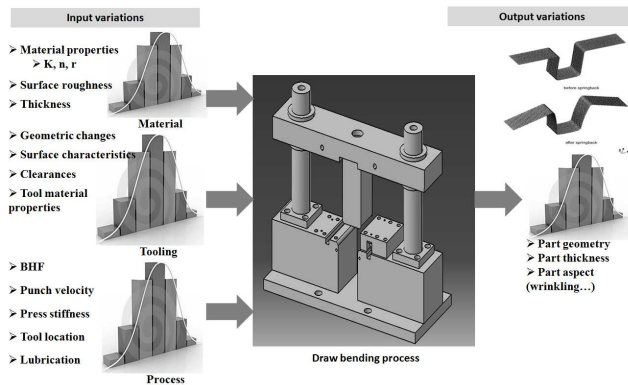


Figure 1: Uncertainty and variation sources in the sheet metal forming process [Nguyen et al., 2013]

However, the sensitivity of finite element models in manufacturing process simulation is not always sufficient to take into consideration very small variations of the input parameters. Indeed, a FEM numerical model always has a threshold at which it is insensitive to the very small variations, consequently the outputs are not confident. So the input parameters' minimum variation step used in the DOE has to be pointed out so as to get reliable responses. Therefore, qualifying the high-fidelity of the FEM numerical model before executing the uncertainty propagation is required. In other words, identifying the minimum sensitivity threshold at which the FEM numerical model returns the reliable results should be done. As a result, the variation step in the DOE must be larger than this determined minimum sensitivity threshold of the FEM numerical model. The focus of this paper is to propose a method for determining the minimum sensitivity threshold to solve the mentioned problem. Furthermore, the influence of input param-

eters in sheet metal forming process on springback is also determined from these results of minimum sensitivity threshold identification.

2 NUMERICAL SIMULATION OF SHEET METAL FORMING PROCESS

As mentioned above, the FEM numerical simulation is the solution for shortening the lead-time and saving the cost for the physical experiments. Nevertheless, the FEM numerical simulation itself is a finite precision and depends on the quality of modeling. There is still difference between results from numerical simulations and results from physical experiments. The cause of the difference may be due to inconsistent FEM models or incorrect inputs parameters or deviation of the input variables [Jansson et al., 2008]. Even though the geometry and the material properties of the tools and the sheet blank are fixed, the variations in the method of FEM modeling by users may lead to various results [Lee and Yang, 1998]. 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. He and Wagoner investigated the impact of the finite element mesh system of the blank on springback results using the same benchmark problem [He and Wagoner, 1996]. The effect of the dynamic term on springback was evaluated by Chung et al. [Chung et al., 1998]. Numerical factors affecting springback including contact damping parameter, penalty parameter, blank element size, number of corner elements were investigated by Lee and Yang [Lee and Yang, 1998]. 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. 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 [Li et al., 2002]. Xu et al. analyzed the effect of sensitivity 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 is researched [Xu et al., 2004]. 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 determination of sensitivity threshold of numerical simulation when having the very small variations of the input parameters of the real sheet metal forming process.

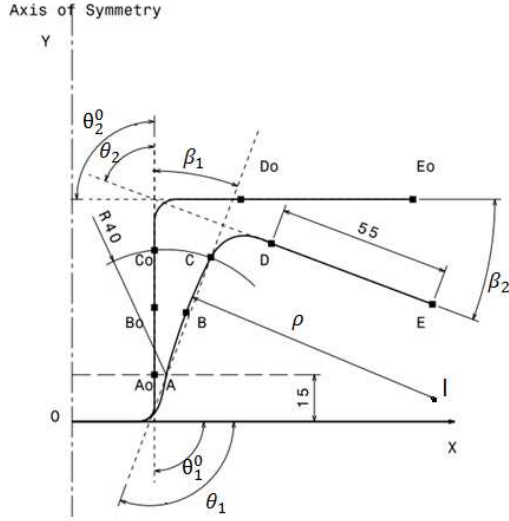


Figure 3: A schematic view of springback profile and parameters.

which the tools have been removed. They are then used to calculate the wall angle (θ_1) and the flange angle (θ_2) 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.

The equations (1 \rightarrow 13) presents the equations for calculating the springback angles and the side wall curl radius.

$$\theta_1^0 = \arccos \left(\frac{\vec{o}\vec{x} \times A\vec{o}B\vec{o}}{|\vec{o}\vec{x}| \times |A\vec{o}B\vec{o}|} \right) \quad (1)$$

$$\theta_2^0 = \arccos \left(\frac{\vec{o}\vec{x} \times A\vec{o}B\vec{o}}{|\vec{o}\vec{x}| \times |A\vec{o}B\vec{o}|} \right) \quad (2)$$

$$\theta_1 = \arccos \left(\frac{\vec{o}\vec{x} \times A\vec{B}}{|\vec{o}\vec{x}| \times |A\vec{B}|} \right) \quad (3)$$

$$\theta_2 = \arccos \left(\frac{A\vec{B} \times D\vec{E}}{|D\vec{E}| \times |A\vec{B}|} \right) \quad (4)$$

$$\beta_1 = \theta_1 - \theta_1^0 \quad (5)$$

$$\beta_2 = \theta_2^0 - \theta_2 \quad (6)$$

$$\rho = \sqrt{(x_A - x_I)^2 + (y_A - y_I)^2} \quad (7)$$

Where,

$$x_I = \frac{(b_2 - b_1)}{\left(\frac{1}{a_2} - \frac{1}{a_1}\right)} \quad (8)$$

$$y_I = b_1 - \left(\frac{x_I}{a_1}\right) \quad (9)$$

$$a_1 = \frac{y_B - y_A}{x_B - x_A} \quad (10)$$

$$b_1 = \frac{y_B + y_A}{2} + \frac{x_B + x_A}{2a_1} \quad (11)$$

$$a_2 = \frac{y_C - y_A}{x_C - x_A} \quad (12)$$

$$b_2 = \frac{y_C + y_A}{2} + \frac{x_C + x_A}{2a_2} \quad (13)$$

2.2 Numerical modeling of draw bending process

2.2.1 FEM modeling

Observations from experimental measurements have shown that the part profiles remains symmetric during the manufacturing process [Huh et al., 2011], so only half of the draw bending model in 3D Finite element numerical model of draw bending of U-shaped part has been built to determine the springback responses with key characteristics shown as in Table 3. Illustration of springback response analyzed with the input parameters' nominal value is shown in Figure 4.

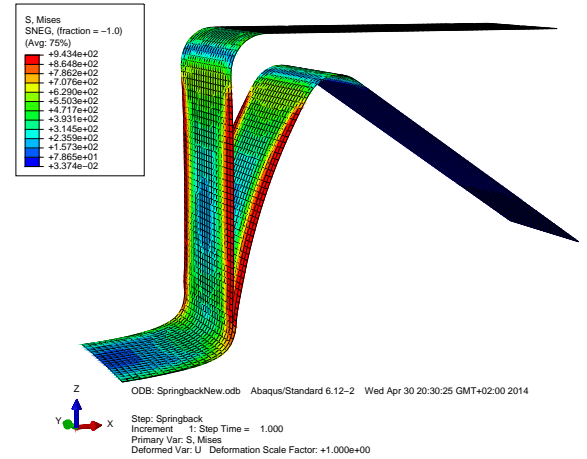


Figure 4: Illustration of springback response analyzed with the input parameters' nominal value

3 IDENTIFICATION, QUANTIFICATION AND UNCERTAINTY PROPAGATION

3.1 Proposed methodology

To investigate the minimum sensitivity of the numerical simulation tools to the input's variations in predicting the variability of the formed sheet metal parts, in this section, an approach is suggested to determine the sensitivity threshold of the numerical model by using the finite difference method.

The finite difference method utilizes the Taylor series expansion to approximate the derivatives. We derive

Name of the FEM code	ABAQUS 6.12.2
General aspect of the code	3-D draw bending: Dynamic explicit Spring-back: Static implicit
Basic formulations	3-D draw bending: Updated Lagrangian formulation with associated flow rule Hill-1948 quadratic yield function Isotropic hardening rule under the plane stress condition
Element type	Blank: Shell S4R, 4-node doubly curved shell, reduced integration, hourglass control and finite membrane strains, 7 integration points through thickness with Simpson integration rule Tools: analytical rigid surface
Number of elements	Blank: 2709
Contact property model	ABAQUS/Explicit: Penalty contact enforcement ABAQUS/Standard: No contact occurs
Friction formulation	Basic Coulomb friction model (penalty method)
Hardening rule	Isotropic, Swift model $\bar{\sigma} = K(\varepsilon_0 + \varepsilon_p)^n$
Yield function/Plastic potential	Hill48, anisotropic creep stress ratios: R11=1, R22=1.05, R33=0.98, R12=0.97, R13=1, R23=1

Table 3: The key characteristics of FEM numerical simulation

an approximation for the first derivative of the function f by first truncating the Taylor polynomial:

$$f(x + \Delta x_i) = f(x) + \nabla_i f(x) \Delta x_i + R_1(x) \quad (14)$$

Where, $\nabla_i f$ is the i -th component of the gradient Δf and Δx_i represents the design perturbation, and $R_1(x)$ is a remainder term. The above is solved for $\nabla_i f(x)$:

$$\nabla_i f(x) = \frac{f(x + \Delta x_i) - f(x)}{\Delta x_i} - \frac{R_1(x)}{\Delta x_i} \quad (15)$$

Assuming that $R_1(x)$ is sufficiently small, the approximation of the first derivative of f or the forward difference approximation is:

$$\nabla_i f(x) = \frac{f(x + \Delta x_i) - f(x)}{\Delta x_i} \quad (16)$$

The backward difference approximation is similarly obtained as:

$$\nabla_i f(x) = \frac{f(x) - f(x - \Delta x_i)}{\Delta x_i} \quad (17)$$

The central difference approximation:

$$\nabla_i f(x) = \frac{f(x + \Delta x_i) - f(x - \Delta x_i)}{2\Delta x_i} \quad (18)$$

Where,

$f(x + \Delta x_i)$: response function of forward bound

$f(x)$: response function of central value

$f(x - \Delta x_i)$: response function of backward bound

Δx_i : variation step of an input variable

The illustration of the finite difference method is presented as in Figure 5.

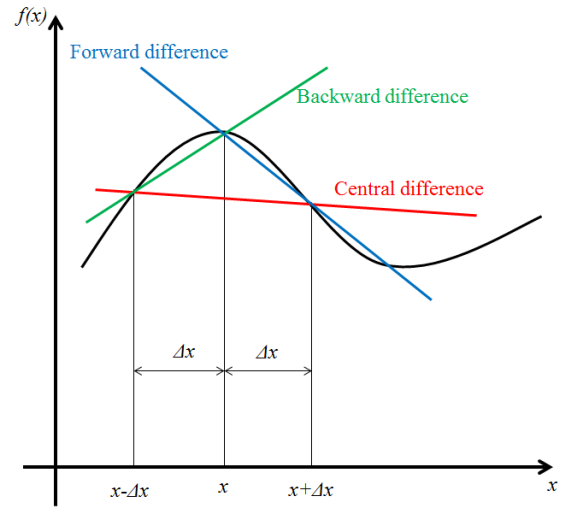


Figure 5: Different geometric interpretations of the first-order finite difference approximation related to forward, backward and central difference approximation.

In mathematical aspect, the idea of the proposed method to identify the minimum sensitivity threshold in FEM numerical simulation of the sheet metal forming process is derived from the tangent line (derivative) as the limit of secants, in other words, when variation step Δx_i gradually decreases and approaches asymptotically zero, then the secant lines approach the tangent line.

The three secant lines are calculated according to the approximations of the first derivative of the finite difference method. In particular, the springback responses are considered as response functions, and the secant lines are the derivatives of the springback responses with respect to variation step of an input variable. In numerical aspect, FEM numerical simulation tools always exist a threshold at which they are not sensitive to the very small variations of the inputs. In other words, the secant lines diverge at

the smaller values of the variation step. Due to the fact that for an analytical function the forward, central and backward difference approximation initially diverge at the greater step size and converge to the same limit as the step size Δx_i approaches asymptotically zero. However, this is no longer true for a FE numerical response function due to finite precision of numerical models. The technique for detecting the minimum sensitivity threshold:

The minimum sensitivity threshold of FE numerical model is identified at a value of variation step where the forward, backward and central difference approximation converge.

4 EXAMPLE OF APPLICATION

4.1 Identification of minimum sensitivity threshold

The springback responses including β_1 , β_2 and ρ are considered as the response functions. They are respectively computed according to the finite difference method as shown in Section 3.1. The minimum sensitivity threshold results of FE numerical sheet metal draw bending when having variation step of sheet thickness from 20% to 0.01% around its nominal value of 1.4 mm determined from 25 computer runs are shown in Figure 6, 7, 8.

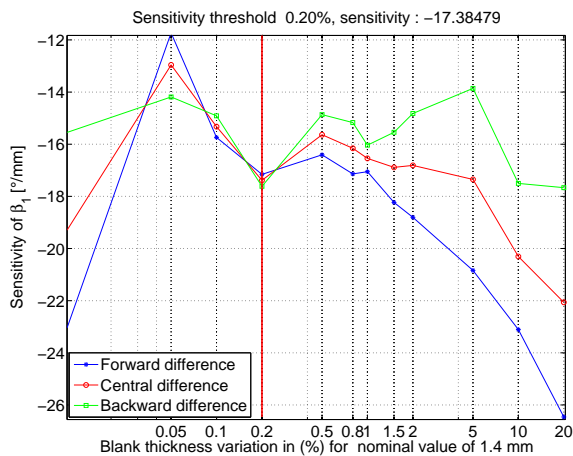


Figure 6: The minimum sensitivity threshold of FE numerical sheet metal draw bending regarding β_1 when having the blank thickness variations from 20% to 0.01%.

It can be seen from the Figure 6 that three forward, backward and central difference approximations regarding the springback angle of β_1 initially diverge from the point of 20%, subsequently are gradually close to together at the point of 1% and converge at the point of 0.2%. After this point, they diverge at the point of 0.1%, they continue diverging at the point of 0.05% and then changing according to arbitrary di-

rection. It is claimed that the minimum sensitivity threshold of FE numerical model regarding β_1 when having uncertainty of blank thickness is 0.2%. Similarly, the difference approximations of the angle β_2 in Figure 7 converge at the point of 0.8%, afterwards they diverge from this point till the point of 0.01%. It is said that the minimum sensitivity threshold regarding β_2 reaches to 0.8%. In the similar detecting technique, the sensitivity threshold of side wall curl radius ρ is at 0.1% as shown in Figure 8. The derivatives of springback responses with respect to blank thickness variation steps initially diverge from the point of 20% and comes close to together at 1% as well as at 0.5%. They converge at the point of 0.1%. The sensitivity points which are closest to each other are considered as minimum sensitivity threshold. The sensitivity curves of springback responses are not smooth and sharp due to the behaviour of non-linear response functions of FE numerical models.

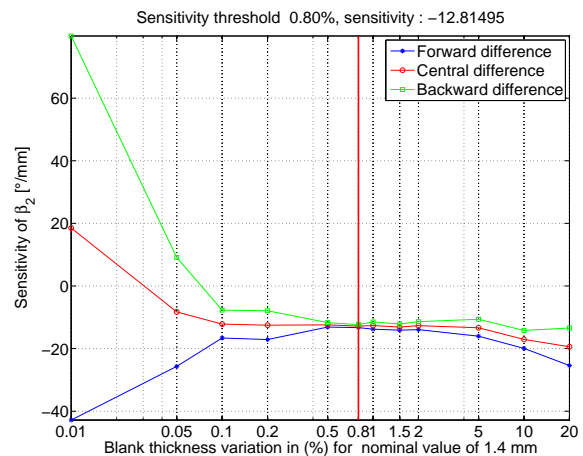


Figure 7: The minimum sensitivity threshold of FE numerical sheet metal draw bending regarding β_2 when having the blank thickness variations from 20% to 0.01%.

According to the proposed reasons, this shows that FEM numerical simulation is not sensible to very small variation step of blank thickness, in particular variation step of nominal values smaller than 0.2%, 0.8% and 0.1% respectively corresponding to the angles of β_1 , β_2 and side wall curl radius ρ . As a consequence, numerical responses of this FEM model are unreliable when the interval of blank thickness variation are smaller than 0.8% around its nominal value. Meaning that the FEM numerical simulation does not get confident responses with blank thickness of 1.4 ± 0.0112 mm in this case study. Furthermore, the local sensitivity of springback responses in terms of blank thickness variation is also inferred from these sensitivity results. As can be seen from Figure 6,7, 8, the local sensitivity of wall opening angle β_1 , the flange angle β_2 and the side wall curl radius ρ is 17.38479°/mm, 12.81495°/mm and 144.55225

mm/mm when blank thickness is 1.4 mm. It shows that the blank thickness influence significantly on the springback responses. With similar reasonings, the

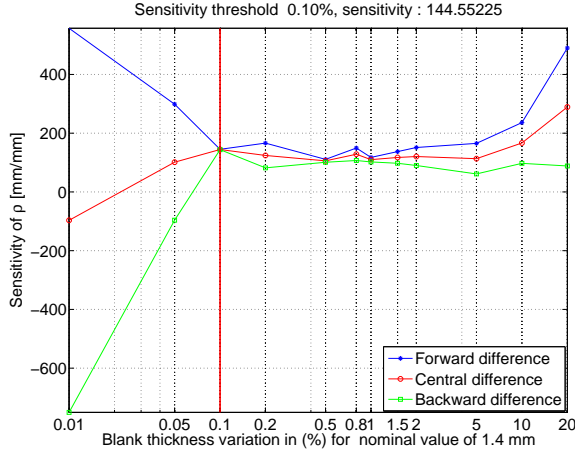


Figure 8: The minimum sensitivity threshold of FE numerical sheet metal draw bending regarding ρ when having the blank thickness variations from 20% to 0.01%.

minimum sensitivity threshold of seven parameters including blank thickness, yield strength, ultimate tensile strength (UTS), blank holder force (BHF), friction coefficient, die radius and punch radius is synthesized in Table 4. The synthesis of the seven in-

Parameter	Sensitivity threshold regarding β_1 (%)	Sensitivity threshold regarding β_2 (%)	Sensitivity threshold regarding ρ (%)
Blank thickness	0.2	0.8	0.1
Yield strength	1	5	5
BHF	1.5	5	1.5
Friction coeff.	1.5	5	5
Die radius	0.2	5	1
Punch radius	1	5	10
UTS	2	5	2

Table 4: The synthesis of the seven input parameters' minimum sensitivity threshold

put parameters' general minimum sensitivity threshold and corresponding variation range are shown in Table 5.

4.2 Sensitivity analysis

In order to identify the influence of input parameters on springback, sensitivity analysis is carried out. Sensitivity functions for the input parameters are calculated as follows:

Parameter	General sensitivity threshold (%)	Corresponding variation range
Blank thickness	0.8	$1.4 \pm 0.0112(mm)$
Yield strength	5	$550 \pm 27.5(MPa)$
BHF	5	$2940 \pm 147(N)$
Friction coeff.	5	0.1 ± 0.005
Die radius	5	$7 \pm 0.35(mm)$
Punch radius	10	$5 \pm 0.5(mm)$
UTS	5	$840 \pm 42(MPa)$

Table 5: The synthesis of the seven input parameters' general minimum sensitivity threshold and corresponding variation range

- For the wall opening angle β_1 :

$$S_i = \frac{\partial \beta_1}{\partial x_i} \xi x_i^{nom} \quad (19)$$

- For the flange angle β_2 :

$$S_i = \frac{\partial \beta_2}{\partial x_i} \xi x_i^{nom} \quad (20)$$

- For the side wall curl radius ρ :

$$S_i = \frac{\partial \rho}{\partial x_i} \xi x_i^{nom} \quad (21)$$

where x_i is the i th input parameter; ξ is variation percent and x_i^{nom} is the i th input parameter at nominal value. Sensitivity analysis results of the input variables contributing to the springback responses of β_1 , β_2 , and ρ are presented in Figure (9, 10, 11). As can be clearly seen from Figure 9 blank thickness and ultimate tensile strength are pointed out as two parameters having the greatest influence on the wall opening angle β_1 , followed by yield strength, punch radius, friction coefficient, blank holder force and die radius in which the effect of die radius is quasi-null. Also, the influence of blank thickness accounts for 52% of the overall variation of the flange angle β_2 , followed by UTS with 34%, BHF and die radius with 5%. Whereas the effect of friction, punch radius and YS is trivial. The variation of the side wall curl ρ is significantly contributed by blank thickness, UTS and die radius with 47%, 31% and 10% respectively. While the influence of YS, BHF, friction and punch radius is quite low in this case. Overall, it is found that taking the uncertainty of blank thickness and material properties scatter (YS and UTS) into account in the early process design for controlling their influences on stamped part performance contributes significantly to reduction of scrap rate. In order to

reduce the effects of inherent variability of the sheet, material properties and tooling geometry, searching optimal configurations of controllable variables consisting of BHF and friction condition should be done.

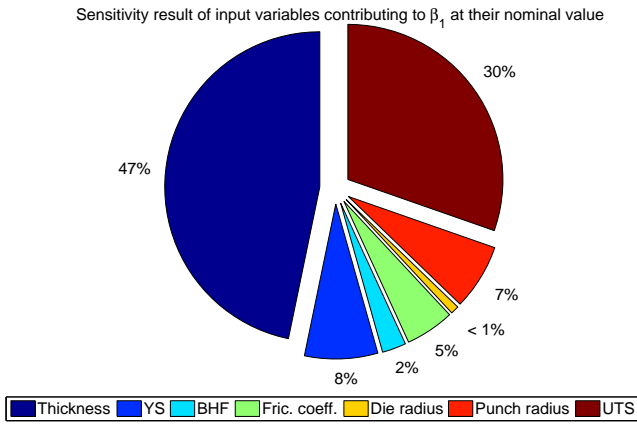


Figure 9: Sensitivity analysis result of the input variables contributing to β_1 at their nominal value

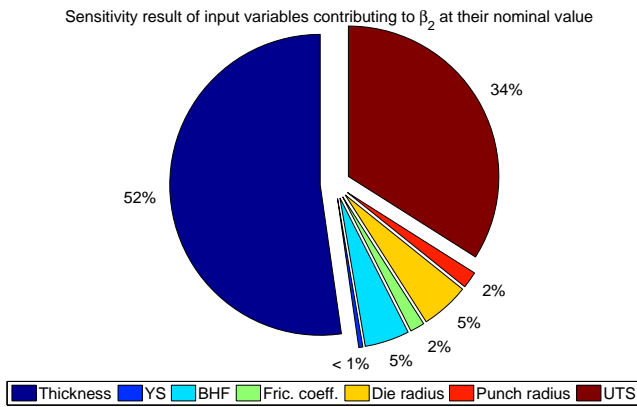


Figure 10: Sensitivity analysis result of the input variables contributing to β_2 at their nominal value

5 CONCLUSION AND PERSPECTIVES

In this paper, a finite difference-based method for identifying the minimum sensitivity threshold of FEM numerical sheet metal forming simulation is proposed. This method has been successfully applied for finding the minimum sensitivity threshold of FEM numerical sheet metal draw bending, a benchmark problem of Numisheet 2011, when having small variations of the blank thickness, material properties, blank holder force, friction coefficient and tooling geometry. Observation from the sensitivity analysis has shown that the main factors influencing substantially on the springback responses are blank thickness and material properties, followed by blank holder force, friction condition and tooling geometry. From the minimum sensitivity threshold results, the minimum variation

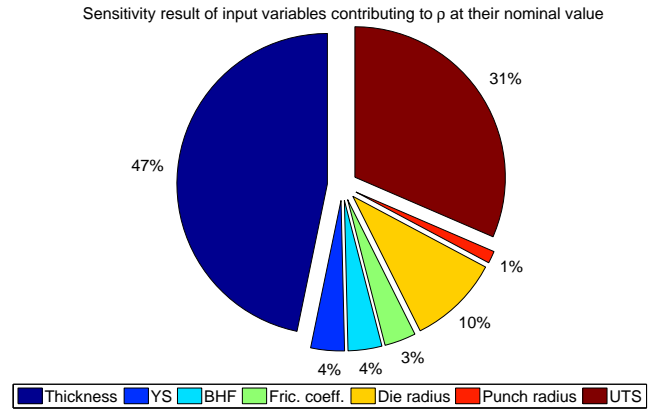


Figure 11: Sensitivity analysis result of the input variables contributing to ρ at their nominal value

step of the input parameters can be used in the DOE when carrying out uncertainty propagation to achieve reliable results from FE numerical simulation as follows:

- Blank thickness: $1.4 \pm 0.0112(mm)$
- Yield strength: $550 \pm 27.5(MPa)$
- Blank holder force: $2940 \pm 147(N)$
- Friction coefficient: 0.1 ± 0.005
- Die radius: $7 \pm 0.35(mm)$
- Punch radius: $5 \pm 0.5(mm)$
- Ultimate tensile strength: $840 \pm 42(MPa)$

One of the significant effects on the quality of the springback prediction is constitutive model of the material. It is an important factor which influences on the minimum sensitivity threshold of FEM numerical simulation. Therefore, in the future work advanced constitutive models need to be adopted in the springback prediction such as the Geng-Wagoner hardening law and the Yoshida-Uemori hardening law which have been proven to describe the springback behavior best [Geng and Wagoner, 2000], [Yoshida and Uemori, 2003].

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