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Research Paper

Parametric investigation of the effect from controlling variables on thermal deformation during stamping process in automotive body part

Beomjoon Choi[a], Junghwan Choi[a], Soojeong Heo[b], Seungwon Shin[c,*]

[a] Department of Mechanical Engineering, Hongik University, Seoul 04066, Republic of Korea
[b] Advanced Body Manufacturing Engineering Team, Hyundai Motor Company, Republic of Korea
[c] Department of Mechanical and System Design Engineering, Hongik University, Sangsu-dong, 72-1, Mapo-gu, Seoul 04066, Republic of Korea

HIGHLIGHTS

- Effect from several variables on thermal deformation is investigated numerically.
- DOE was performed to identify controlling variables and its interactional effect.
- Ambient temperature has significant effect on final thermal deformation.
- Effect from controlling factors is non-uniform over the target surface.
- Controlling initial blank temperature is effective for reducing thermal deformation.

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ABSTRACT

The purpose of this study is to analyze the thermal deformations that degrade the quality of assembled products through the stamping process. Special attention was paid to the ambient temperature change in the manufacturing process of automotive body part. First, we found that ambient temperature, which is the external condition and difficult to control, can be varied significantly due to seasonal change thus it can be an important factor for the deviation from thermal deformation. Important controlling factors for thermal deformation were identified and their effects on final dimensional changes were carefully analyzed by the design of experiments (DOE) procedure. Based on DOE result, we found that the influence of each controlling factor was non-uniform across the target surface. To understand the local variation clearly, vectorized plot of the thermal deformation was introduced for visualization. Locations vulnerable to thermal deformation have been identified and it was confirmed that ambient temperature change has significant effect especially on those weak spots. Finally, we tried to reduce the deviation from thermal deformation by controlling the initial temperature of the mold and the blank. We found that controlling the initial blank temperature was more effective.

1. Introduction

The stamping process is one of the most widely used manufacturing techniques for the production of automotive body parts. During stamping process, several deviation factors could be presented which is lowering final product quality. There have been various attempts to improve product quality in the industry. Due to the complexity associated with the actual stamping process, most efforts have been limited to passive aspects of the process control that adjust the apparent input conditions such as feed rate of the target material or punching pressure etc. based on previous experiences. Detailed physical phenomena during stamping process should be identified to control final dimension of the product more precisely. Among various factors, deviations from thermal deformation are particularly difficult to estimate. The changes of the temperature are influenced by various sources during complicated manufacturing process so the thermal deformation from such temperature changes is very hard to anticipate theoretically or measure experimentally. In this aspect, numerical simulation can be appropriate choice as investigating tool for thermal deformation of the product during stamping process.

Archard [1] first theoretically confirmed that energy loss due to friction was converted to heat during stamping process. Kim et al. [2] conducted a finite element analysis (FEA) on performance of various lubricating oils for mold, which affect the moldability of the product in the stamping process. Both stress and temperature variation during the stamping process were considered. Groche et al. [3,4] studied adhesive

* Corresponding author.
E-mail addresses: cb8878@naver.com (B. Choi), power_y@naver.com (J. Choi), soojeong.heo@hyundai.com (S. Heo), sshin@hongik.ac.kr (S. Shin).

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wear effect between blank and mold during the stamping process using finite element analysis (FEA). They also investigated the effect from the shape of the mold considering both thermal and mechanical load during the process. Pereira and Rolfe [5] conducted a study on temperature changes in blank and mold during stamping using commercial finite element analysis (FEA) program (ABAQUS). They identified that the properties of the blank and the molding speed can influence the maximum temperature generated during the stamping process. Most researches so far have been focused on analyses with simple objects. The stamping process was also simplified for detailed analysis of the effect from specific control variables. Actual stamping process in industry is composed of highly complex processes. Therefore, it is necessary to model the complicated stamping process appropriately to predict the amount of thermal deformation accurately.

In our previous research [6], numerical model was developed to analyze and predict the thermal deformation specifically targeting an automotive body part. Complicated stamping processes associated with automotive body part have been modeled as several sub-steps. Developed numerical procedure was benchmarked by comparing temperature distribution measured from experiment. Even though a variety of studies on the stamping process are possible using developed numerical models, focus has been paid to numerical model development and analysis on the basic results such as stress and temperature distribution over the product after typical stamping process. However, there are too many factors affecting dimensional variation through thermal deformation and these factors are interrelated each other through complicated processes. Therefore, even if we developed an appropriate numerical model and investigated detailed physical behavior of a typical stamping process in the previous study, there was a limit to a complete understanding the influence of the various deviation factors. In order to overcome these limitations and to make comprehensive studies on the factors affecting the temperature-modulated dispersion of the product, it is necessary to select and analyze the characteristics of the various influential factors more systematically.

It is practically infeasible to perform complete analysis from numerous input conditions affecting thermal deformation. Many similar engineering problems have been solved through the method of design of experiments (DOE). The feature of the design of experiments (DOE) is that it can effectively analyze the individual or cross-related influence from many important factors. Many engineering problems utilized design of experiments procedure to test sensitivity and interaction from related input conditions. A few examples are: Yoon et al. [7] used the design of experiments to characterize the main design factors affecting the warping of the ultra-thin solar cell, and at the same time, presented optimal design conditions. Likewise, Carton and Olabi [8] conducted a design of experiments to optimize the performance of the fuel cell. We can also find cases of solving problems by using design of experiments (DOE) closely related to current study. Ledoux et al. [9] investigated the effects of the interaction between the clearance and the wear state of the tool. They also studied the effect from sheet metal thickness on the evolution of the blanking force and the geometry of the sheared profile using design of experiments (DOE). They proposed an efficient and cost-effective way of modeling and analyzing the relationships that describe process variations. Pairel et al. [10] used design of experiments (DOE) to predict and improve the spring-back deformation in the stamping process. In addition, design of experiments (DOE) has been widely used in various engineering fields, mainly for the purpose of deriving optimal design and performance of product [11–13].

Main objective of the current study is to investigate the effect from several input variables on the thermal deformation during stamping process of the automotive body part. The friction coefficient, ambient temperature, holder distance, upper pressure, and punch pressure were considered as input variables. Previously developed and benchmarked numerical method for general stamping process of the automotive body part [6] was adopted to investigate the thermal deformation. To identify the major controlling variables, design of experiments (DOE) procedure was utilized. Interaction of the control variables was also analyzed in detail. Based on these results, it would be possible to understand the comprehensive impact of the control variables, which could have a significant effect on the thermal deformation of the designated product. In addition, a design guideline is proposed to maintain the thermal deformation of the final product within the manageable tolerance.

2. Numerical method

In current research, we tried to utilize the previously developed numerical procedure for stamping process. The code has been developed for specific stamping process in automotive industry. And it was benchmarked for its accuracy with actual stamping process by comparing temperature distribution from actual measurement. Here we will briefly summarize the key features of the numerical procedure for current reader. Detailed numerical model, simulation settings, and construction can be found in our previous paper [6].

First, the three-dimensional meshes were generated using commercial software HYPERMESH based on the geometrical information of the CAD model. The simulation geometry consists of four different parts, which is Upper, Blank, Holder, and Punch (see Fig. 1(a)). Devices of Upper, Holder, and Punch can be categorized as the mold and the blank will turn into final product after the stamping process. A numerical model capable of thermal deformation analysis was constructed using a commercial software ABAQUS using Dynamic, Temperature Displacement and Explicit Finite Element models. Both the blank and mold surfaces have been modeled as elastic body. Physical properties from Pereira and Rolfe [5] were utilized to prescribe material fields with realistic stress-strain relation provided by the manufacturer.

The relative motion between mold surfaces and the blank will generate heat, which causes thermal deformation. Both frictional and plastic heat generation have been considered in this research. In ABAQUS, frictional heat generation is modeled as follows:

$$Q = \eta\tau\dot{s} = \eta\tau\frac{\Delta s}{\Delta t} \quad (1)$$

Here, η describes the heat conversion rate from frictional energy loss, τ is the frictional stress, Δt is the incremental time, and Δs is the incremental slip, respectively. We used default value of 0.9 for η. On the other hand, heat flux generated from plastic deformation (r^{pl}) can be considered using following equation:

$$r^{pl} = \eta'\sigma\dot{\varepsilon}^{pl} \quad (2)$$

Here σ is the stress tensor and $\eta'$and ε^{pl} represents inelastic heat fraction and rate of plastic straining, respectively. We also used a default value of 0.9 for η'. More detailed explanations for the numerical model and setup can be found in [6].

In order to analyze the accurate stamping process, whole process has been sub-divided into 6 steps as shown in Fig. 1(b). Step 1 is a primary fixing step where the Holder is raised then the blank becomes fixed between the Upper and the Holder. In the step 2, lower Punch is raised up for the first impression of the blank. In the step 3, A second fixing step in which the blank is fixed between the Upper and the Holder, step 4 is a second impression step where the lower Punch pressure is increased to the full compression. In step 5, the blank becomes released from the mold then the blank cooled down from convection at step 6. The produced part after step 6 is cooled down to ambient temperature until thermal equilibrium is reached. The boundary condition and the loading condition applied to each sub-step was adjusted to emulate the actual movement of the equipment. The moving speed of the molding devices used in the stamping process was carefully analyzed to obtain right boundary conditions.

Next, developed numerical model was verified its accuracy by comparing with experimentally measured data. Detailed benchmarking procedure for the numerical model has been depicted in Fig. 2. Step I