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Automobile Roof Panel Forming: Prediction and Compensation of Springback and Application of Numerical Simulation Based on Dynaform

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Abstract

The forming of sheet metal in a desired and attractive shape is a process that requires an understanding of materials, mechanics and manufacturing principles. Manufacturing a consistent sheet metal component is challenging due to the nonlinear interactions of various material and process parameters. One of the major issues in the manufacturing of inconsistent sheet metal parts is springback. Springback is the elastic strain recovery in the material after the tooling is removed and the final shape of the product depends on the springback amount formed. In this study according to the result of simulation the inverted compensation method is adopted to optimize die surface design. Similarly, to predict and compensate the springback error this study presented an analytical approach of forming process in a stepwise modification of the automobile roof panel. Moreover, based on Dynaform and finite element analysis of sheet metal stamping simulation the sprinback in automobile roof panel is predicted and compensated. In addition, this study examines the significant requirements of the sheet metal forming precision of automobile body and the simulation of forming, stamping and springback of automobile roof panel is carried out, and the result of simulation also is analyzed.

Keywords

Springback, Sheet Metal Forming, Dynaform, Finite Element Method (FEM), Auto Roof Panel

1. Introduction

In automobile part manufacturing and production process to establish the geometry of a part depending on the shape, the material deformation ability and the process condition without any problem, it is absolutely essential to specify the part material property as well as understanding of the materials parameter. This helps to figure out the limit to which the part material can be formulated without reaching any kind of fracture and deformation.

With the competition of worldwide automobile industry, the forming of auto body panels becomes more important for the increasing requirements of appearance and feasibility. Due to the variety and complexity of auto body shape and its forming process, the traditional methods of qualitative analysis and "trial and error" method are not suitable for the development of modern automotive industry. However, in die making industries the trial and error method cannot vanish. As several scholars reason out that the utilization of traditional method in die making industries is because of the consideration of die deformation [1]. The present leading global automotive manufacturers have been challenged with applying traditional design practices to sheet metal design and assembly. The goal behind this effort is to help achieve high quality auto bodies with minimal lead-time and development costs. Nevertheless, nowadays modeling and simulation are often integrated parts of product and process design in an integrated modernized manufacturing environment.

In sheet metal forming process modeling and simulation can be used for various purposes, such as to predict material flow, to analyses stress, strain and temperature distribution, to determine forming forces, to forecast potential sources of defects and failures, to improve part quality and complexity, to reduce manufacturing costs as well as predicting and eliminating the springback problem. Markedly, springback usually affect the appearance and the quality of the parts. Similarly, it brings different kinds of problems on the geometry, design, assembly and on the final shape of the parts by increasing the tolerance and clearance of the subsequent part forming operation. Consequently, to reduce springback in a sheet metal forming process, it is absolutely essential to apply modeling and simulation in the designing phase.

"The springback is mainly an elastic deformation which occurs after sheet metal forming processes, when the formed part is removed from the forming tools. The springback changes the part's geometry so it can cause difficulties during a subsequent assembly process, or cause the twisting in the assembled part. An accurate prediction of springback of formed sheets is of vital importance for the design of tools in automotive and aircraft industries" [2].

From time to time the issue of springback becomes the major concerns of automobile part manufacturing industries. During the last decades extensive studies attempted to find the way to reduce the springback and determine the controlling factors. Particularly, numerous studies in springback have been conducted on different domain, such as Young's modulus [3], elastoplastic constitutive equations [4], advanced high strength steel (AHSS) [5] [6] [7], through-thickness integration of stress [8] and so on.

Springback is often correlated with the yield stress of steels, the higher the flow stress the greater the springback. Additionally, in a sheet metal forming operations springback will not totally eliminate, there is at least some value of it that is called free springback. Indeed, different scholars investigate different experimental studies to evaluate, predict and compensate springback, which is the common problem of automobile part manufacturing process that involves sheet metal fabrication. For instance, to predict springback in sheet metal forming process scholars investigated a new finite strain model by combining both non-linear kinematic and isotropic hardening [9]. Identically, several scholars investigated the ultra-high strength steel (UHSS), "a widely used steel in automotive structural components to further reduce the weight of the auto body and improve the crashworthiness performance" [10], based on a new kinematic hardening model and inertia relief approach to predict and compensate the springback.

Correspondingly, Livatyali and Altan presents the laboratory experiments on prediction and elimination of springback in straight flanging, in which the influence of process variables, such as die shoulder radius, punch nose radius, punch-die clearance, material properties and pad force has been discussed [11]. Other scholars also summarized their study using computer-aided design method and finite element method (FEM) to predict and eliminate the springback in straight flanging process [12]. According to the study by Chen and Koç, springback is the value related to many factors, such as material property, die radius, blank holding force, blank thickness, tolerance, friction coefficient, and few others [6], thus, Chen and Koç believes that controlling the springback factors will eliminate the problem.

Automobile body parts are the parts of the most difficult forming in sheet metal forming domain for the characters such as complicated shape, high requirement of surface quality and large outline dimensions. Wrinkle, rupture and springback are sensitive issues to mechanical property of the sheet metal's pressing direction, geometry shape, forming and layout of drawing tendon, and friction and lubrication condition. The development of automobile manufacturing is restricted by these conditions, thus, the manufacturing of automobile body parts need much experience and understanding. Furthermore, the strong demand for shortened development cycle, cost reduction, high quality production with strong sheet metal has required the development of computer aided engineering.

In this study, in order to accurately simulate the forming process of automobile roof panel, the simultaneous stamping, forming and springback analysis are employed. Then the structural forming and springback analysis of an automotive roof panel is carried out and the springback, fracture, and wrinkling factors will be compared using Dynaform simulations.

2. Methodology and Data

This study begins with a brief overview to the necessity of sheet metal forming simulation and the complexity of automobile body panel forming. Followed by Dynaform and finite element analysis, which is a powerful simulation tool for analyzing complex multi-dimensional sheet metal forming problems. After the FEM model set up this study employ Dynaform to calculate and simulate the stamping process of the auto roof panel. Based on the analysis of the calculating results the prediction and optimization of springback error and the inverted compensation method continued. Thereby the quality product is obtained. The major aim of prediction and optimization is to find ideal process parameters and to avoid the forming difficulties, springback, wrinkling and rupture. This study concludes by briefing the repeated simulation and adjustment, the optimum process parameters and the result obtained.

3. Overview of Springback and Other Common Defects in the Sheet Metal Forming Process

In the automotive industry springback is one of the major factor influencing the quality of stamping sheet metal parts. In most dynamic metal forming operations, the nonlinear deformation process tends to generate a large amount of elastic strain energy in the blank sheet. This elastic energy that stored in the blank sheet will release while pressure is removed. This release of energy is the driving force of springback, generally causes the blank to deform towards its original geometry. Hence, the final part shape in a sheet metal forming process depends on not only the contours of the dies, but also the amount of elastic energy stored in the part while being plastically deformed.

Springback is the hotspot focused in the field of sheet metal forming and stamping. It causes the inaccuracy of the part shape so that prediction and compensation of springback is significant to obtain the final desired shape. The part final shape depends on the springback amount formed. If the springback amount exceeds the tolerance allowed, the part size precision become reduced and failed to satisfy the requirement of assembly. In order to compensate the size deviation caused by the springback, it is needed to use the latest automobile sheet metal forming technology rather than traditional try and error die process.

Correcting the die surface repeatedly through the trial and error method brings high cost and low quality, consumes a lot of manpower and material resources. Therefore, to avoid the traditional try-out method the FEM, Dynaform and other updated software and simulation in automotive panel forming research is significant. Current initiatives in automotive industries are driving a need for stronger and lighter automotive panels. A successful sheet metal stamping process converts an initially flat metal sheet into a useful part with the complicated and sophisticated desired shape and without deformation and fracture.

The most frequent types of defects in sheet metal forming process are springback, cracks, wrinkling and scratches [13]. Wrinkling which often occurs near the fringe, inside the blank-holder or on the unsupported sidewall of the stamped part is due to excessive compressive stresses in the plane of the sheet metal that results the bulking of the sheet metal. Cracking on the other hand is nominally caused by excessive tensile stresses in the plane of the sheet metal. Similarly, scratching is caused by the defects of the tool surface.

Accordingly, to accomplish the desired deformation without failure, there are generally two ways to apply, one is to use materials with better properties that able to resist wrinkling and cracking, which needs to develop new materials with high mechanical properties. Second, use materials that can control the strain distribution of the stamped part. The ideal thickness distribution is uniform without excessive compressive strains and excessive tensile strains. Therefore, the metal sheet can provide sufficient strain for the desired shape and does not reach its limit failure criteria.

4. Numerical Simulation of Auto Body Panel Forming

Before discussing the details of the numerical simulation processes, it is necessary to understand the basic concept of simulation. Simulation is the process of designing a model of a real system and conducting experiments with the model for the purpose of understanding the behavior of the system and evaluating various strategies for the operation of the system before production. Furthermore, simulation techniques have significant role in scientific study and occupy important places in education, military, entertainment and almost every field that we can imagine. With the development of computer technology, numerical simulation has been widely used in many fields.

Consequently, the numerical simulation is the simulation part that uses numerical methods in order to represent the quantitative evolution of the real environment and physical system operation. It pays much attention to the physical content of the simulation and emphasizes the goal that forms the numerical results of the simulation. Practically, numerical simulation uses the values that can best represent the real environment and the evolution of the system also strictly obeys the physical laws that govern the real physical processes in the simulation region. Therefore, the result of the simulation can have a good representation of the real environment and from the result of this simulation one can safely draw proper conclusions and have a better understanding of the system.

5. Formability Analysis

Formability is the efficiency of a given sheet metal to undergo a plastic deformation without fracturing and damaging or without any kind of failure. However, the deformation efficiency of plastic of metallic sheet parts is limited to a certain extent at which the part could experience wrinkling, fracture or tearing. The general parameter which indicates the formability of the sheet metal part is the crack or fracture strain determined by uniaxial tensile testing. Additionally, formability depends not only on the properties and parameter of the material but also depends on the process factors in practical forming operation. This paper paid special attention to the forming process factors in the manufacturing of sheet metal domain, such as wrinkling, rupture, and springback. These factors usually occurred in the manufacturing process due to the sheet metal property.

5.1. The Design of Blank Shape and the Direction of Drawing

Most automobile panel shapes are complex and difficult to get through to start the initial blank geometry shape. In addition, the geometric expansion factor does not consider plastic deformation. Practically, variations in material properties, thickness distribution, blank dimensions, environmental conditions and springback properties make the reproducibility and predictability of a blank sheet metal forming process quite difficult.

The selected part is relatively simple design using Dynaform to estimate the stock load and to get directly through the geometric shape of the initial blank sheet metal. The simplified rectangular blank sheet metal shape model shown in **Figure 1** has the maximum die size 30 cm, the smallest cell size 0.5 mm, and the offset rate 0.05 mm mesh parameters.

In actual production, sheet metal (blank shape) is placed on the blank holder and the blank holder is the part that holds the sheet metal while the punch force is applied. Punch is a curved and relatively large degree of bending force placed under the blank holder, bounded by gravity. If the simulation set the blank sheet metal without calculating the shape deformation then it will certainly bring some errors. However, it must first set on top of the mold and calculated after the shape deformation due to gravity. In Dynaform, a module used to calculate the gravity load called the gravity loading. The model shown in **Figure 2** is the calculated result of rough, coarse and a re-refined mesh of the blank sheet metal.

The result shown in **Figure 3** is the blank sheet metal after the gravity load-bounded by gravity to bend.

The analysis of the forming of the auto roof panel should first determine the direction of drawing. Automobile roof panel is the part of the car body, according to its installation position and the consistent order the part should be placed at the roof of the car. In most cases when placing the car body parts automobile companies use the press fit in the convenient direction in order to avoid inconsistent placement of the body parts. Even when designing, choosing the appropriate direction of the drawing will determine the smooth implementation of the

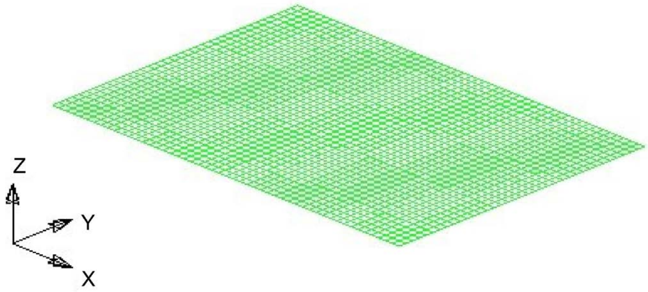

Figure 1. Blank sheet metal outline design.

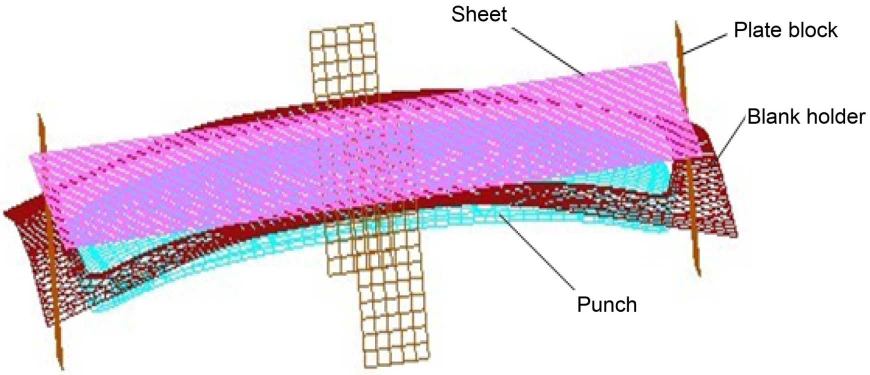

Figure 2. Gravity load simulation.

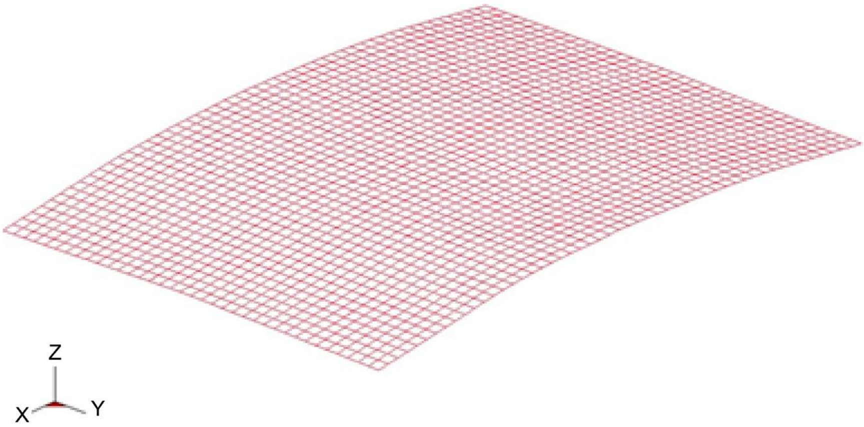

Figure 3. Blank sheet metal after the gravity load.

direction of stamping process. See **Figure 4**.

5.2. Blank Sheet and Mold Parameters

After taking stock of the grid model of gravity loading and further refinement take the grid size 10 mm, the billet steel plate thickness is 0.7 mm and the calculation automatically by the program areas of intense deformation re-division of the minimum mesh size 2 mm. The sheet metal parameters are defined as follows, the sheet metal thickness 0.7 mm, Poisson's ratio (V) 0.3, elastic modulus (E) 207 GPa, tensile strength (TS) 3 MPa, yield strength (σ) 174 MPa,, mass density (ρ) 7.83 × 109 kg/mm^3, strain hardening coefficient (K) 518 MPa, thickness anisotropy coefficient 1.91, 1.65 and 2.2 and the hardening coefficient (n) 0.242 Pa.

In the molding process stamping simulation of the blank sheet usually set in three phases, such as simulation of the blank holder (closed stage), forming simulation stage and unloading springback simulation stage. In the closing stage, the blank holder must be added before the forming simulation stage, but no blank holder force should be applied, and the drawing type is single action. Moreover, the upper and lower blank holder gap is set to (t) as a blank thickness together and speed is 5000 mm/s. See **Figure 5** and **Figure 6**.

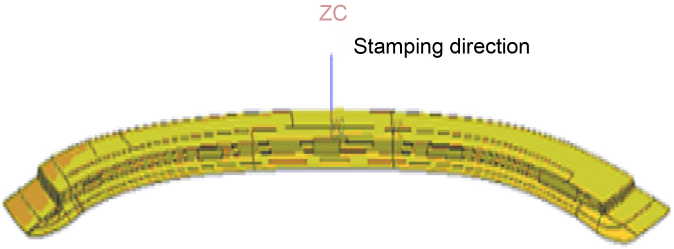

Figure 4. Drawing and stamping direction of auto panel.

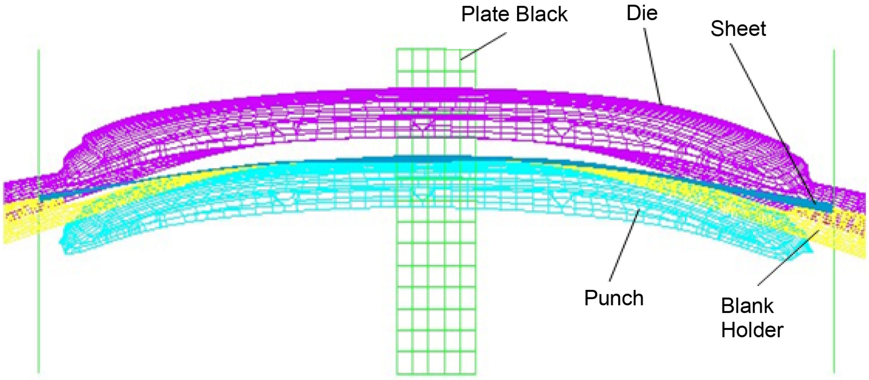

Figure 5. Closed stage simulation of automobile roof panel.

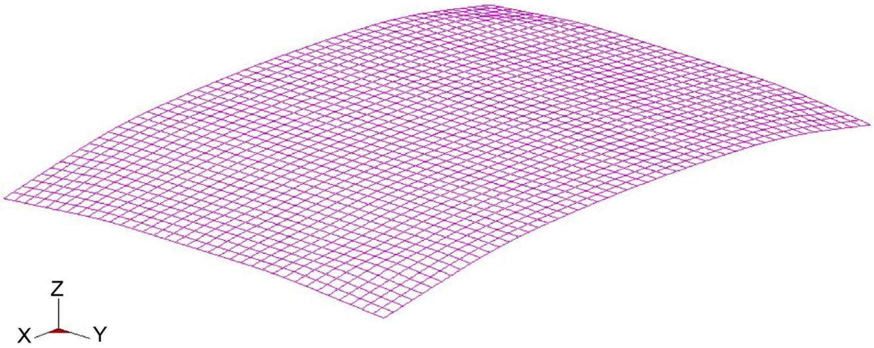

Figure 6. Blank sheet metal stamping simulation after the unloading.

5.3. Addendum

Addendum is a key element in the part of the stamping process design. Stamping direction is determined by the direction of drawing to meet the requirements of the implementation process. However, the vast majority of auto body panel which requires stamping are determined by the shape, contour or depth of addendum designed draw bead. Advanced stamping process design is an important indicator whether the addendum parts directly affects the drawing process while the deformation parameters rough conditions applied. The size of deformation, the deformation distribution, surface quality, cracking, wrinkling and other problems are the indicator of design failures. Addendum should be designed to comply with the car body panel complementarily with the whole surface part, in a simplified structure and attractive enough. See Figure 7 and Figure 8.

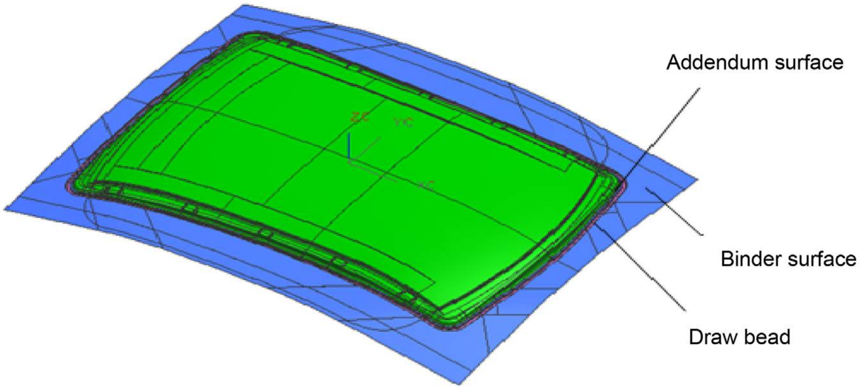

Figure 7. Simulation model of automobile roof panel.

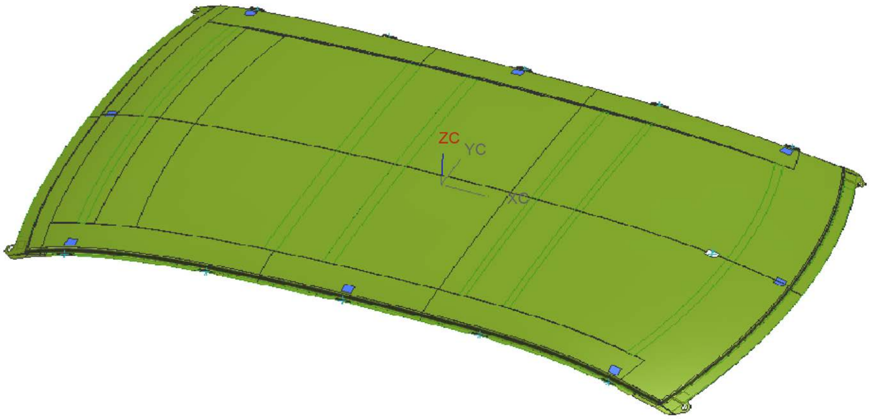

Figure 8. Stamping process design of auto roof panel with addendum at the fringe.

6. Forming Simulation Results

The forming simulation in the automotive industry is used to optimize and develop the sheet metal component parts efficiently. Similarly, the sheet metal forming simulation is an accurate and effective simulation in the entire forming operation and it also helps to predict the prevention of springback. Furthermore, the forming limit diagram (FLD) is a convenient and often used tool for the classification of the formability and evaluation of the forming process of sheet metal. The forming limit of sheet metal represents in the forming limit diagram (FLD) and it distinguishes the various deformation states of the part. For instance, (**Figure 9**) FLD indicates that the auto roof panel has a small amount of tendency of wrinkling and risk of crack near the fringe of the panel, whereas the rest areas are in a secure zone.

Similarly, the simulation result clearly demonstrates that the major portion of the formed auto roof panel is in a "safe zone". Although there are some insufficient wrinkling and stretch near the auto roof panel bar and fringe, those defects would not affect the normal operation of the formed panel as they are not in the functional region. Accordingly, the simulation result indicates that the auto roof panel has a good formability part.

Figure 9. Forming limited diagram—FLD (Modified tooling of forming simulation result).

On the other hand, the thickness distribution of the blank after forming shown in **Figure 10**, demonstrates some insufficient wrinkling pressure at the fringe of the panel surface. This insufficient wrinkling pressure comes through the subsequent trimming process. However, the impact of this insufficient wrinkling pressure on the forming part is negligible. Therefore, one can conclude that there is no apparent wrinkling in the forming process found except near the fringe of the panel a slight material accumulation occurs.

Furthermore, forming thickness distribution is not equally distributed and the drawing sheet deformation is not uniform, but still within the limit that most of the regional thickness are between 0.524 - 0.721 mm. Similarly, as can be seen in **Figure 10**, the maximum thinning ratio of the formed auto roof panel is about 25% that is within the normally acceptable range of 3% to 25%.

In sum, the difference between the initial and the final thickness is small and panel deformation and strain are also insignificant. Although forming thickness distribution is not equally distributed, some parts which will inevitably lead the panel to springback and rupture are negligible.

Similarly, (both **Figure 10** and **Figure 11**) simulation result indicates that the part plastic deformation is sufficient and thinning and springback amounts are small among most areas. There is no crack and wrinkling in the forming process and it indicates that the part plastic deformation is uniform and the rigid requirement is ensured. Therefore, the forming simulation results proved that there is no quality defect in the car roof panel forming process.

7. Analysis and Result

The auto roof panel is one of the largest areas covering the driver and the passenger compartment. In the modern automobile manufacturing there are several different types of car roof panels such as, solid metal stationary hard tops, sun roofs, panoramic glass roofs, retractable hard tops, and few others, each of them are unique in design and function. Obviously, roof panel is the most important

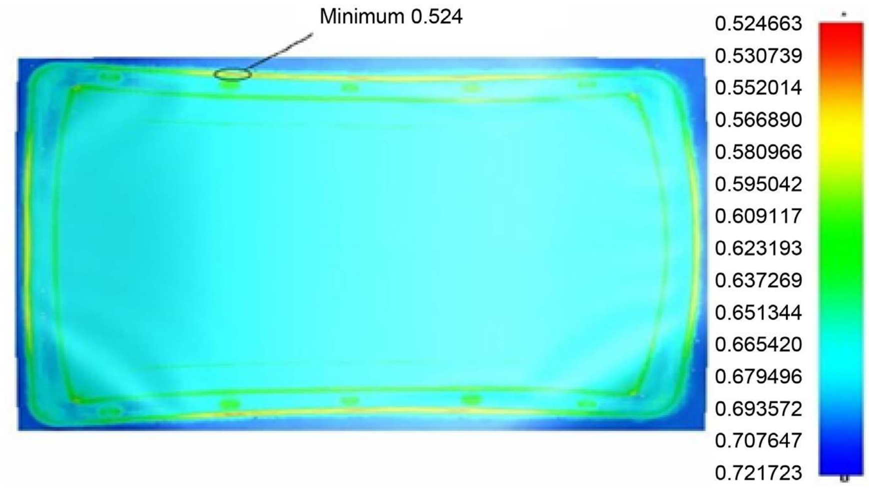

Figure 10. Thickness distribution.

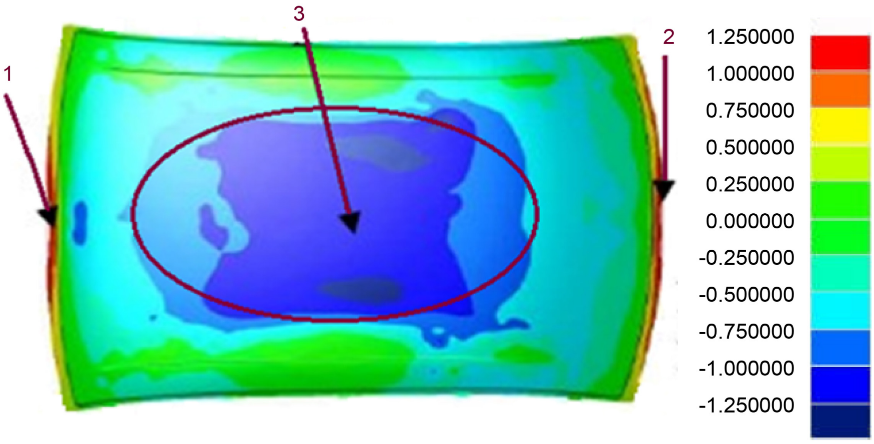

Figure 11. Springback simulation result of roof panel.

part that protects the automobile inner compartment from unfriendly environment. There are regulations regarding the amount of the force that the roof panel withstands in case of damage or collusion to sustain without causing injury to the occupants'.

Other than the crashworthiness of the roof panel there are also manufacturing imperfections. As most of scholars described springback is a common manufacturing imperfections phenomenon in every sheet metal manufacturing process and it is a geometrical change of the part after the forming tool force has removed and occurs at the end of the forming process [5] [10] [14]. Particularly, Ablat and Qattawi explicitly mention that "Springback refers to the phenomenon of elastic recovery of sheet metal upon unloading during a forming operation" [15].

To solve the problem of springback numerous scholars developed different types of methods, however there are some of the methods which most of scholars agreed and approved. The first method is to use an effective and viable tool called finite element analysis (FEA) for the prediction of springback and residual stress [5] [16]. The second method is optimizing and controlling the sheet metal forming parameters [17] such as contact friction, forming temperature, tool radius (R/t), blank holder force, and others. The third method is compensation, one of the effective methods for limiting and controlling the impacts of springback and residual stress. The forth is the property of the material, it is clearly evident that springback varies linearly with the yield strength, which is the material of higher yield strength have higher springback [18].

Consequently, it can be concluded that the ductile materials have less springback effect than the brittle materials. It is also possible to reduce the amount of springback by increasing the sheet metal thickness. Moreover, in the bending operation the residual stress slightly causes the sheet metal to springback problem, therefore, it is necessary to over bend the sheet metal in a precise amount to achieve the desired bending angle and bending radius [19].

Springback Simulation Result

On the bases of the quality of sheet metal forming springback is a very significant factor to influence the forming process. Sheet metal stamping process simulation is a fundamental aspect for the prediction and compensation of springback. Apparently, an accurate prediction, compensation and elimination of springback are vital for the sheet metal forming design tools. Almost 90% of the automobile parts are made from sheet metal forming this makes the sheet metal forming the most difficult operation in the stamping process domain.

As can be seen from **Figure 11**, the tendency of the springback displacement distribution with the color code in three differently marked areas, such as Area 1, 2 and 3 indicates that both "Area 1 and 2" displacement of springback is upward, which is a positive direction movement. This illustrates that both Area 1 and Area 2 of the auto roof panel is rising (swelling) upward by 1.56 mm. On the other hand, the "Area 3" displacement of the springback is opposite to both the Area 1 and Area 2 movement, which indicates that Area 3 has a negative springback displacement by 1.5 mm.

Moreover, as the color code indicates the value of springback movement varies in between ±1.25 mm, this concludes that the roof panel surface quality and final assembly precision will be influenced by the springback amount. Therefore, the springback prediction and compensation must be taken. The following figure (**Figure 11**) demonstrates that the springback displacement distribution simulation and the calculated result of auto roof panel by the static implicit algorithm.

The surface of the two Arias are rising upward that needs to be designed in the reverse direction along the springback displacement by 1.56 mm, accordingly, both Areas will compensate to a zero springback. However, Area 3, because it is sagging at the middle of the roof panel, the surface is designed to rising in reverse direction along the springback sagging movement by 1.5 mm and compensated to zero springback. See **Figure 12**.

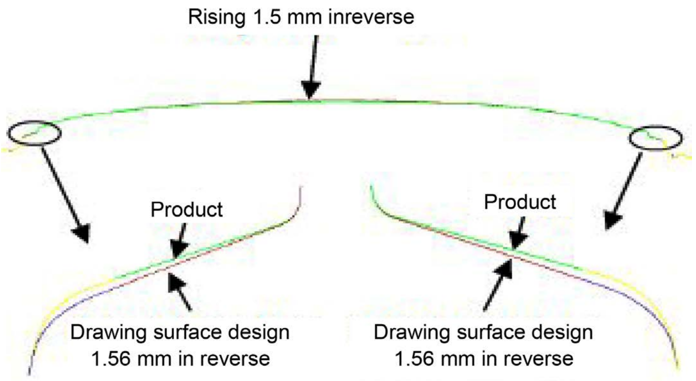

Figure 12. 1-2 section result of automated springback compensation compared with the target geometry.

8. Conclusions

The sheet metal stamping process contains a variety of complex phenomena, such as collision, friction, corrosion, elastic-plastic deformation, and few others. Accordingly, the sheet metal behaviors lead complex quality control difficulties to the design of sheet metal and forming. Generally speaking, the forming parts mainly measured their performance based on the three quality defects such as, wrinkling, rupture and springback. One of the most difficult defects is springback control. Clearly, different materials properties as well as different shapes have various springback amounts. As a result, springback problem will affect the shape and size of precision stamping parts and surface quality; not to mention that the final shape of the auto body panel depends on the amount of springback. When the springback exceeds the sufficient limit the formation of defects will affect the automobile assembly.

In the sheet metal stamping and forming process there are different ways to predict, compensate or eliminate the springback problem. This study analyzed the prediction and compensation of springback error based on Dynaform forming, stamping and springback simulation algorism. The result articulately indicated that the quality problem does not exist in the forming and stamping process of auto roof panel, but appeared in the springback process. However, the amount of the springback was insignificant. Accordingly, this study obtained the actual and qualified auto roof panel and the experiment test results proved that the springback control measures are rational and the simulation prediction and surface compensation methods are accurate.

Biographical Statement

Amsalu K. Addis has a Master of Engineering degree and currently completing his Ph.D. in the School of Economics and Management at Fuzhou University, Fuzhou, China.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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