Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 31
ISSUE 2
December
2008

Applicability valuation for evaluation of surface deflection in automotive outer panels

D.H. Park [a,*], W.R. Bae [a], H.J. Jeong [a], B.S. So [a], T.J. Ko [b], P.K.D.V. Yarlagadda [c]
[a] Gyeongbuk Hybrid Technology Institute, 300 Sampung-dong, Gyeongsan-si, Gyeongbuk 712-210, Korea
[b] School of Mechanical Engineering, Yeungnam University, 214-1 Dae-dong, Gyeongsan-si, Gyeongbuk 712-749, Korea
[c] School of Engineering Systems, Queensland University of Technology, 2 George Street, Brisbane QLD 4001, Australia
* Corresponding author: E-mail address: pdh@ghi.re.kr

Received 10.09.2008; published in revised form 01.12.2008

Analysis and modelling

ABSTRACT

Purpose: Upon unloading in a forming process there is elastic recovery, which is the release of the elastic strains and the redistribution of the residual stresses through the thickness direction, thus producing surface deflection. It causes changes in shape and dimensions that can create major problem in the external appearance of outer panels. Thus surface deflection prediction is an important issue in sheet metal forming industry. Many factors could affect surface deflection in the process, such as material variations in mechanical properties, sheet thickness, tool geometry, processing parameters and lubricant condition.
Design/methodology/approach: Numerical simulation of process was performed by the use of finite element method, paying attention particularly to the thickness distribution and surface deflection of the drawn outer panel and the outline flange during forming. Simulation procedures of automotive outer panel as large size shape are as follows; 1) Acquisition of drawing parts 2) Laser scanning for generating CAD model 3) CAD model generation 4) Simulation model operation 5) Simulation execution and analyses of simulation results.
Findings: The development of automation in stamping and assembly processes of automobile manufacture will require an excellent surface quality of formed panels and also their accurate dimensions.
Practical implications: The use of high strength steel sheets in the manufacturing of automobile outer panels has increased in the automotive industry over the years because of its lightweight and fuel-efficient improvement. But one of the major concerns of stamping is surface deflection in the formed outer panels. Hence, to be cost effective, accurate prediction must be made of its formability. The automotive industry places rigid constraints on final shape and dimensional tolerances as well as external appearance quality of outer panels. The numerical simulation makes it possible to design and optimize the total process to a level, which can't be reached by traditional theoretical and experimental methods.
Originality/value: Computer simulations can be used to determine the influence from variations in material properties and process parameters.
Keywords: Surface deflection; Automotive outer panels; Press forming; Sheet metal forming industry; Finite Element Method

1. Introduction

The press forming processes are frequently used in the automotive industry, the packaging industry, and the household appliances industry to manufacture products with more complicated shapes and curvatures. Nowadays, the automotive industry tends to favor light construction principles, leading to the usage of light materials, tailored blanks and usage of new production processes such as hydroforming, and hot forming. The deep drawing process is one of press forming processes applied with the intention of manufacturing a product with a desired shape and no failures [1-4]. The final product shape after deep drawing is defined by the tools, the blank and the process parameters. An incorrect design of the tools and blank shape or an incorrect choice of material and process parameters can yield a product with a deviating shape or with failures. A deviating shape is caused by elastic springback after forming and retracting the tools. The most frequent types of failure are wrinkling, necking, scratching. Wrinkling may occur in areas with high compressive strains, necking may occur in areas with high tensile strains, scratching is caused by defects of the tool surface. The deformation patterns of the sheet material are influenced by the material properties and the friction conditions. The friction conditions during forming depend on the lubricant, the presence of coatings on the blank, surface roughness of the tools and the blank and blank holder pressure.

Upon unloading in a stamping process there is elastic recovery, which is the release of the elastic strains and the redistribution of the residual stresses through the thickness direction thus producing springback [5-6]. Springback causes changes in shape and dimensions that can create major problems in the assembly. Sheet metal is simply metal formed into thin and flat pieces and is one of the fundamental materials used in press working. From a press working point of view, the characteristics of steel sheets made by various steelmakers can be broadly classified into sheets designed for strength rather than formability. Because there is no clear correlation between the mechanical properties of steel sheets and their formability, it is not possible to accurately determine formability of a particular type of steel sheet. The characteristics of sheet metal forming processes are fabricated from steel sheet, which is in contact with the surface of the deforming material and tools. It can produce parts with high degree of dimensional accuracy and increased mechanical properties along with a good surface finish. The popularity of sheet metal forming is mainly due to its high productivity, relatively low assembly costs and the ability to offer high strength and lightweight products. Surface defects such as surface deflection, springback, and wrinkles are most serious problems in the press forming of high strength steel sheets into automobile outer panels [7-13]. In this research the pattern and origin of surface defects in outer panels are investigated and classified based on both the mechanisms by which surface deflection occurs in automotive outer panels for implementing industrial application of surface defects.

2. Classification of surface deflection

The appearance and quality requirements for automobile outer panels are increasingly critical in recent years. In the forming of large outer panels, the deformation behavior of sheet in the die cavity is delicate and complex due to a number of factors, including the non-simplicity of panel shapes and the low rigidity of sheets, so that it is extremely difficult to handle the behavior quantitatively. In order to answer the increasing requirements for better surface formation accuracy of automobile outer panels, it is important to clarify the factors governing geometrical surface defects on the pressed panels, and to find the methods for improvement. The factors which control surface deflections include yield strength, sheet thickness, n value, and r value on the material site, and application of pressure, tension from the press forming technical site. Surface defects on a pressed panel are classified into those produced under loading and upon unloading. The former, arising from deflection produced in the course of pressing and retained until after detachment from the die, is represented by wrinkles or local bends. The latter, caused by a difference in elastic recovery due to a non-uniform stress distribution in the course of pressing, have their mechanical base composed of buckling or springback phenomena.

Small defects on the surface of sheet metal stamping parts may have significant impact on the optical appearance of the final product after finish treatment. Usually a quantitative value for such surface defects like surface deflection lies between 25 to 250 microns in depth and a few millimeters in size for dents. Fig. 1 demonstrates the fundamental shape of surface defect. If a surface defect lies on a flat surface, such a deflection is relative easy to be localized by the current technique. However, most outer panel stamping parts in automotive industries, such as door panel etc. is not a flat surface, they are usually a curved surface, and a deflection on a curved surface becomes difficult to be identified by the current technique.

The size of surface deflection in the automobile outer panels is influenced mostly by the strength and yield point of the steel sheet in particular. The yield strength has a large influence on fitting behavior over the whole range, particularly on maximum wrinkle height, easiness of wrinkle absorption and the length of punch travel after disappearance of wrinkle. When mild steel sheet and high strength steel sheet are formed under the same conditions, the size of surface deflection that occurs in the high strength steel is larger than that occurring in the mild steel.

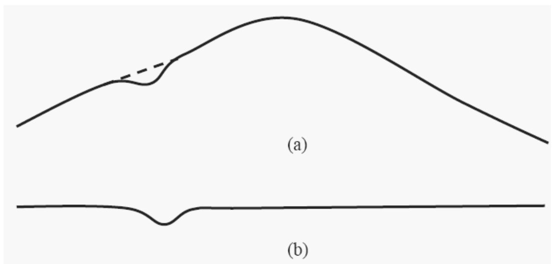

Fig. 1. Fundamental shape of surface defect; a) Shape containing both contour and surface defect; b) Shape after removing the contour information

Mechanisms of surface deflection occurrence are follows approximately;

(1) Local compressive stress from non-uniform metal flow during loading.

(2) The non-uniform distribution of the elastic recovery strain at unloading.
(3) Deflection of the springback at unloading due to the difference in shape rigidity of the panel.

During press forming, surface deflection barely reveals itself due to the tension that works on the sheet, but when the press forming is ended and the outer panel is relieved from press forming, the surface deflection reveals itself in the form of surface bending as a result of the non-uniform plastic deformation that occurs in the thickness direction of the panel during the press forming.

3. Surface deflection evaluation

3.1. Simulation procedures and models

The finite element method as a powerful numerical technique has been applied in the past years to a wide range of engineering problems. Although much FE analysis is used to verify the structural integrity of designs, more recently FE has been used to model fabrication processes. When modeling fabrication processes that involve deformation, such as sheet metal forming, the deformation process must be evaluated in terms of stresses and strain states in the body under deformation including contact issues. The major advantage of this method is its applicability to a wide class of boundary value problems with little restriction on work piece geometry. Without extensive knowledge of the influences of all these variables on sheet metal forming process, it is hardly possible to design the tools adequately and make a proper choice of blank material and lubricant to manufacture a product with the desired shape and performance. As a result, after the first design of the tools and choice of blank material and lubricant, an extensive and time consuming trial and error process is started to determine the proper tool design and all other variables, leading to the desired product. This trial and error process can yield an unnecessary number of deep drawing strokes, or may even require redesigning the expensive tools. To reduce this waste of time and cost, process modeling for computer simulation can be used to replace the experimental trial and error process. To design or select the tools and the equipment, such design essentially consists of predicting material flow, determining whether it is possible to form the part without surface or internal defects, and predicting strains and stresses necessary to execute the forming operation.

Metal forming processes are characterized by large displacements and rotations, strong non-linearity, complex contact problems and complex tool geometries. This rapid development both with regard to speed, accuracy and with regard to areas, which can be covered by simulations, will further increase the potential for industrial use of computer simulations in the areas of forming. It becomes possible to determine the relationship between material property and the forming process. In other words numerical simulation makes it possible to design and optimize the total process to a level, which can't be reached by traditional theoretical and experimental methods. Computer simulations can be used to determine the influence from variations in material properties and process parameters. Currently, the accuracy and reliability of numerical simulations of sheet metal forming processes do not yet satisfy the industrial requirements. The surface deflection around a hollow is so little that the defect is scarcely detected visually or by oilstone touching by experienced inspectors. The surface deflection potentially exist during forming are amplified by elastic recovery after removing a panel from dies. The elastic recovery is inhomogeneous around the hollow because of the non-uniform plastic deformation. Therefore extensive research in the field of surface deflection is necessary to decrease the existing gap between the real-life sheet metal forming process and the predictions obtained from simulations. Numerical simulation of process was performed by the use of finite element method, paying attention particularly to the thickness distribution and surface deflection of the drawn outer panel and the outline flange during forming. Simulation procedures of automotive outer panel as large size shape are as follows; 1) Acquisition of drawing parts 2) Laser scanning for generating CAD model 3) CAD model generation 4) Simulation model operation 5) Simulation execution and analyses of simulation results. Fig. 2 shows drawing part of hood outer panel and Fig. 3 shows laser scanning machine for generating CAD model. Fig. 4 shows CAD model generation from laser scanning data and Fig. 5 shows simulation model of hood outer panel for performing simulation. Fig. 6 shows flow chart of forming simulation.

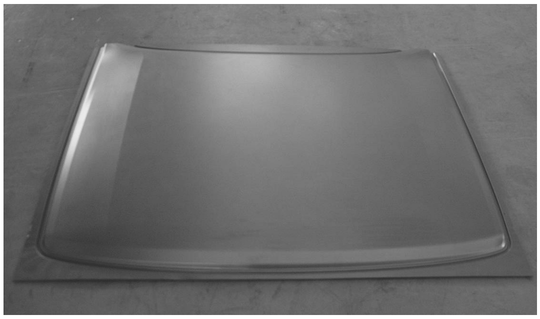

Fig. 2. Drawing part of hood outer panel

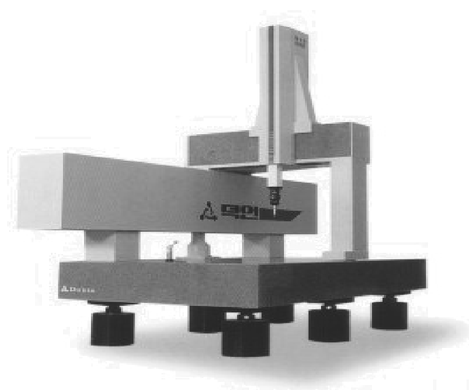

Fig. 3. Laser scanning machine for generating CAD model

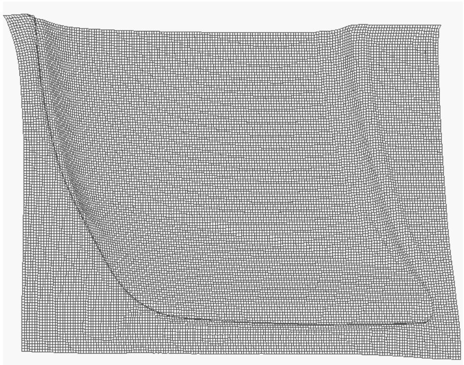

Fig. 4. CAD model generation from laser scanning data

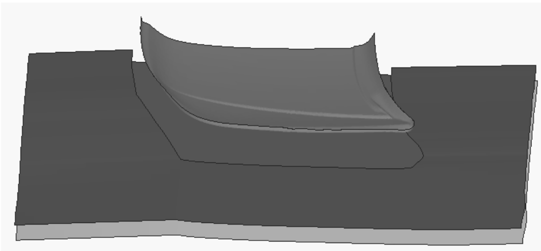

Fig. 5. Simulation model operation for simulation execution

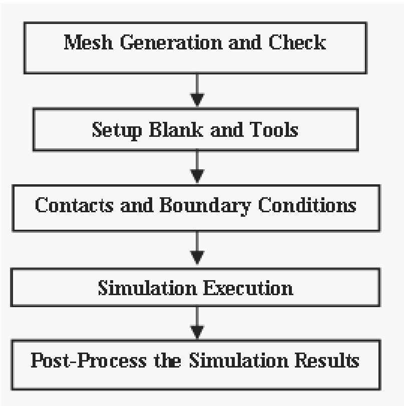

Fig. 6. Flow chart procedures of forming simulation

3.2. Forming limit diagram

Sheet metal can deform only to a certain level before a localized zone of thinning or necking occurs. This level is dependent mainly on the combination of the ratio of major and minor strains. Keeler (1965) first introduced the Forming Limit Diagram (FLD). Keeler's work was limited to conditions of biaxial stretching, i.e. when both major and minor principal surface strains were positive. Goodwin (1968) extended Keeler's work to include the tension-compression principal strain region. This combined diagram is now well known as the Keeler-Goodwin forming limit diagram. The FLD is widely used in industry as a guide on the formability of sheet metal deformation processes.

The plane deformation resulting from the forming of a sheet metal workpiece can be measured by using an array of small diameter circles, printed on the blank surface in the critical strain regions. The circles deform into various shapes during forming, the major and minor axes indicate the direction of the major and minor principal strains. This circular grid technique of measuring strains can be used to diagnose the causes of necking and fracture in industrial practice and to investigate whether these defects were caused by variations in the properties of the material, wear of the tools, changes in lubrication, or incorrect press settings.

During forming these circles are distorted into ellipses. Measurements of the major, d1, and minor, d2, diameters after deformation are made to find the principal strains. Fig. 7 shows a scribed circle grid before and after deformation. These may be expressed as true strains, $\varepsilon 1 = \ln (d1/d0)$ and, $\varepsilon 2 = \ln (d2/d0)$ or engineering strains, $e1 = (d1-d0)/d0$ and $e2 = (d2-d0)/d0$. Sheets pre-marked with circle grids can be formed by either prototype tools during die tryout or by production tools. Local strains near failures or suspected trouble points can be measured and the nature of the problem can be identified. Fig. 8 shows a stamped part with the deformed point pattern.

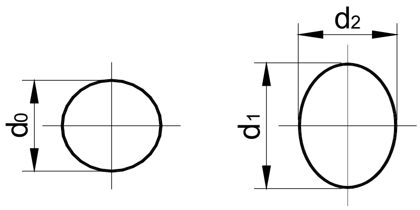

Fig. 7 Scribed circle grid before and after deformation; a) Before deformation, b) After deformation

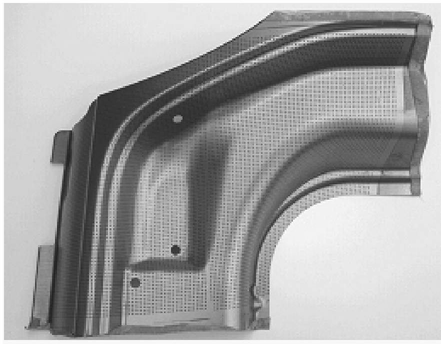

Fig. 8 Stamped part with scribed grid pattern

4. Industrial examples

4.1. Basic model for analyzing surface defect

Surface deflection is one of the most difficult problems in applying high strength steel and general steel sheet to automobile outer panels. Particularly, the effects which elastic recovery exerts on the mechanism and on the extent of the occurrence of surface deflection in actual panels must be clarified and quantified. This is undoubtedly essential to establish systematic means of avoiding surface deflections and improving the mechanical properties of steel sheets for automobile use. For the reduction of surface deflection in press forming, tension balance control, an increased stamping load, etc. can be used. The appearance and quality requirements for automobile outer panels are increasingly stringent in recent years. To meet these requirements, it is necessary to determine quantitatively the surface formation accuracy, which has not been determined so far, and to establish quickly a new evaluation of press forming severity dealing with both fracture and surface formation accuracy.

In the forming of outer panels, the deformation behavior of sheets in the die cavity is delicate and complex due to number of factors, including the complexity of panel shapes and the low rigidity of sheets, so that it is extremely difficult to handle the deformation behavior quantitatively. Therefore, various processes for the control of surface deflections can be found from the viewpoint of both material properties and press forming techniques. We think the most important and common factors responsible for the initiation of surface deflection are the non-uniform distribution of stress during forming, and surface deflections caused by elastic recovery, which occurs in the outer panel of forming process due to non-uniform elastic recovery strain and non-uniform elastic recovery moment. The means of controlling surface deflections may be cited from the viewpoint of material such as stress, sheet thickness, and friction on the sheet steel.

Fig. 9 shows rectangular drawing model which is basic model. To reduce the simulation time and take advantage of the symmetrical shape of the body, only one quarter of the cross-sectional area was simulated. Fig. 10 shows maximum principal stress vectors in the rectangular drawing model with low BHF. Maximum principal stress was observed to be compressive in radial direction and tensile in transverse direction in the flange region. Maximum principal stress was found to be tensile in both radial and transverse direction in the punch head region. In the corners of the punch head, the maximum principal stress was found to be highest but no defects were observed in this simulation result.

4.2. Real autobody model

Surface deflection is one of the most difficult problems in applying high strength steel and general steel sheet to automobile outer panels. Particularly, the effects which elastic recovery exerts on the mechanism and on the extent of the occurrence of surface deflection in actual panels must be clarified and quantified. This is undoubtedly essential to establish systematic means of effectively avoiding surface deflections and improving the mechanical properties of steel sheets for automobile use. For the reduction of surface deflection in press forming, tension balance control, an increased stamping load, etc. can be used as means of reducing surface deflection. The appearance and quality requirements for automobile outer panels are increasingly stringent in recent years. To meet these requirements, it is necessary to determine quantitatively the surface formation accuracy, which has not been determined so far, and to establish quickly a new evaluation of press forming severity dealing with both fracture and surface formation accuracy.

Fig. 11 shows maximum principal stress state at the lower dead point when forming steel under the normal forming condition. In center of the product, maximum principal stress was observed to be tensile in both radial and transverse direction. In flange area of the product, maximum principal stress was observed to be tensile in transverse and compressive in the radial direction. As evident in this figure, the principal stress σ1 direction is rotated so that it is nearly perpendicular to the profile line of the corner area. It is evident that the minor principal stress σ2 is changed to a compressive stress from the corner of right bottom. But the σ2 in the left bottom corner is tensile. The σ2 on the right and left corner is smaller than that on the other side. It was recognized that the principal stress direction rotates and the principal stress reduction begins in the corner at the same time as the forming of the corner area begins.

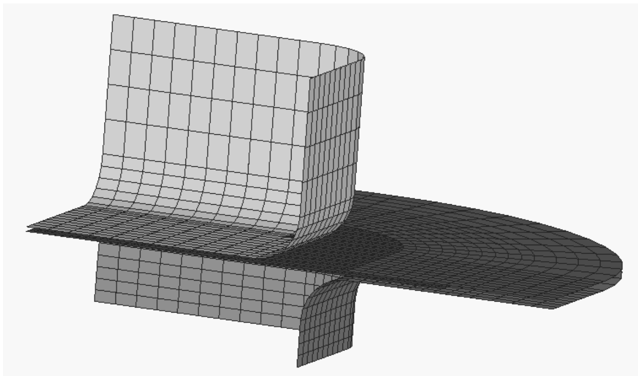

Fig. 9. Rectangular drawing model

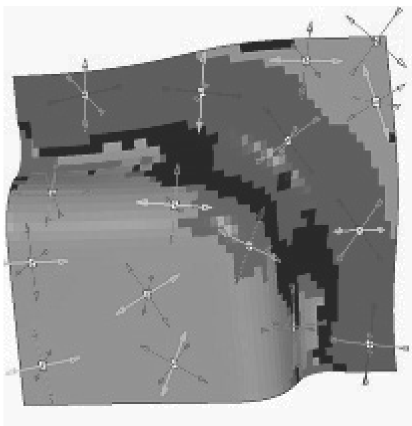

Fig. 10. Maximum principal stress vectors of rectangular drawing model

Geometrical surface defects such as wrinkles, surface deflection and springback are most serious problems in the press forming of high strength steel sheets into autobody outer panels.

The origin of surface deflections in typical autobody panels is investigated by scratching oilstone of the panel using a sensitive spherometer. According to product profile, these surface deflections are roughly classified into those occurring on the peripheries of the embossed region and those occurring near wheel arches. The two types of surface deflections contrast with each other in size and in extent. As compared to the surface deflection attributable to wheel arches, the surface deflection that results from embossing characteristically tends to become acute in shape and large in extent. Fig. 12 shows maximum principal stress vectors at the lower dead point when forming steel under the normal forming condition. At the corner of the product, maximum principal stress was observed to be tensile in both radial and transverse direction. In flange area of the product, maximum principal stress was observed to be tensile in transverse and compressive in the radial direction. As evident in this figure, the principal stress σ1 direction is rotated so that it is nearly perpendicular to the profile line of the corner area.

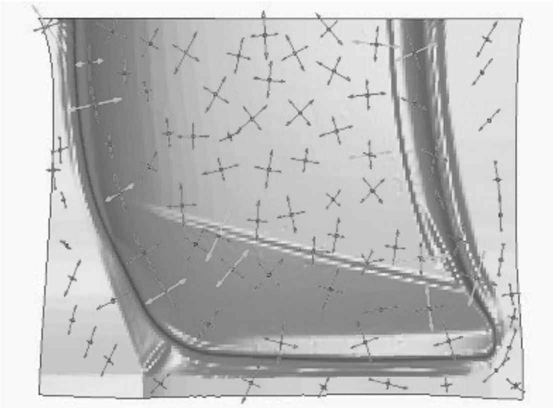

Fig. 11. Maximum principal stress vectors of door outer panel

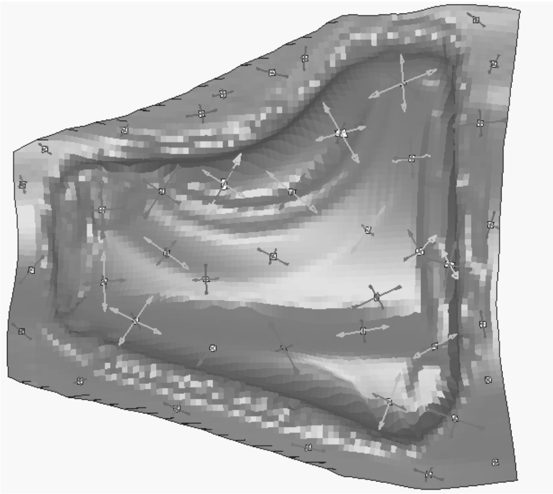

Fig. 12. Maximum principal stress of fender outer panel

From many investigations in the past, the yield strength has been found to be the most influential property on the surface deflection around hollows and corners. More precisely, the flow stress at just formed condition is considered to determine the magnitude of the surface deflection, which suggests that elastic recovery is anisotropy in r value, is reported to affect the surface deflection around door handle hollows. Fig. 13 shows formability diagram of DDQ material and Fig. 14 presents FLD curve of the DDQ material (blank holder force 100ton, friction coefficient μ=0.158). Wrinkle tendency was found to be high in center of the product. The principal stress was observed to be reducing at the corner and center area at the same time as the forming begins. This fact indicates that there is a difference in the principal causes of surface deflection. Specifically, for the corner side, because of the sharp configuration, non-uniform metal flow causes the compressive stress on the corner.

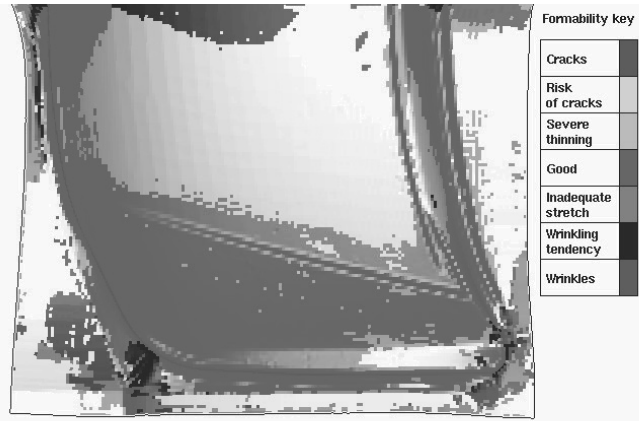

Fig. 13. Formability diagram of door outer panel (DDQ 100ton μ0.158)

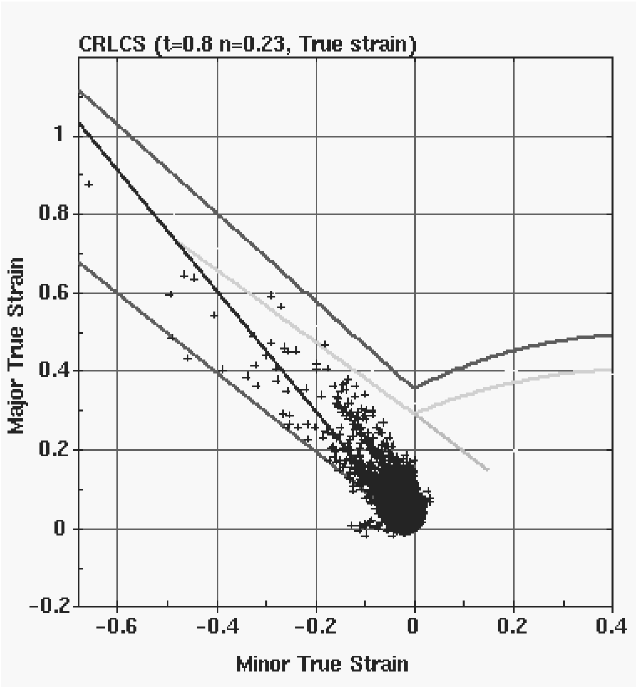

Fig. 14. FLD curve of door outer panel (DDQ 100ton μ0.158)

5. Conclusions

On the progress of sheet metal forming, both the surface defect and the dimensional defect of press formed panels are undoubtedly two of the most important current problems, respectively. The development of automation in stamping and assembly processes of automobile manufacture will require an excellent surface quality of formed panels and also their accurate dimensions. Such a tendency will increase the necessity of sheet metals which have a homogeneous property and a dimensional uniformity. The following various reasons to cause the surface deflection are observed when forming with the analytic model.

(1) The compressive stress that is caused by the non-uniform metal flow in the die cavity.

(2) Deflection is caused by the difference in shape rigidity of the panel.

(3) The mechanism of the occurrence of surface deflection can be classified into two types, plastic and elastic. These two types of surface deflection are classified by most commonly occurring surface deflections in ordinary autobody outer panels, namely the surface deflection around the embossed portion and the surface deflection around the wheel arch respectively.

(4) Basic model and real autobody model analyses for detecting surface deflection were performed. Specially, the size and direction of maximum principal stress and major strain were considered for judging simulation results.

Acknowledgements

This work was supported by the Gyeongbuk Hybrid Technology Institute(GHI), Korea.

References

[1] H.S. Kim, M. Koc, J. Ni, A. Ghosh, Finite Element Modeling and Analysis of Warm Forming of Aluminum Alloys – Validation through Comparisons with Experiments and Determination of a Failure Criterion, Journal of Manufacturing Science and Engineering 128 (2006) 613-621.

[2] F. Paulsen,T. Welo Applications of Numerical Simulation in the Bending of Aluminum Alloy Profiles, Journal of Materials Processing Technology 58 (1996) 274-285.

[3] M. Kawka, A. Makinouchi Shell Element Formulation in the Static Explicit FEM Code for the Simulation of Sheet Stamping, Journal of Materials Processing Technology 50 (1995) 105-115.

[4] P. Ducroco, E. Markiewicz, P. Drazetic, and P Guyon, An Inverse Approach to Determine the Constitutive Model Parameters Using Drop Tests and Numerical Tools, International Journal of Impact Engineering 21 (1998) 433-449.

[5] N. Song, D. Qian, J. Cao, Effective Models for Prediction of Springback in Flanging, Transactions of the ASME 123 (2001) 456-461.

[6] M J Finn, P C Galbraith, L Wu, J O Hallquist, L Lim, T L Lin, Use of a Coupled Explicit-Implicit Solver for Calculating Springback in Automotive Body Panels, Journal of Materials Processing Technology 50 (1995) 395-409.

[7] A. Makinouchi, M. Kawka, Press Simulation in Sheet Metal Forming, Journal of Materials Processing Technology 46 (1994) 291-307.

[8] A. Makinouchi, Sheet Metal Forming Simulation in Industry, Journal of Materials Processing Technology 60 (1996) 19-26.

[9] L. Liu, T. Sawada, M. Sakamoto, Evaluation of the Surface Deflection in Pressed Automobile Panels by an Optical Reflection Method, Journal of Materials Processing Technology 103 (2000) 280-287.

[10] S.K. Esche, S. Khamitkar, G.L. Kinzel, T. Altan, Process and Die Design for Multi-Step Forming of Round Parts from Sheet Metal, Journal of Materials Processing Technology 59 (1996) 24-33.

[11] M. Kawka, L. Olejnik, A. Rosochowski, H. Sunaga, A. Makinouchi, Simulation of Wrinkling in Sheet Metal Forming, Journal of Materials Processing Technology 109 (2001) 283-289.

[12] H. Sunaga, A. Makinouchi, Sheet Metal Forming Simulation System for Predicting Failure in Stamping Products, RIKEN review 14 (1996) 47-48.

[13] H. S. Kim, M. Koc, J. Ni. Determination of Proper Temperature Distribution for Warm Forming of Aluminum Sheet Materials, Journal of Manufacturing Science and Engineering 128 (2006) 622-633.