Analysis of Sheet Metal Forming of Interstitial-Free Steel and Extra-Deep-Drawing Steel Using ABACUS

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Abstract

Sheet metal forming is one of the most important processes in automobile industries. Often the components are formed in multistage. As the plastic deformation is path dependent, the prior deformation affects the capability for further (second stage) deformation without defects. It is further important to know the forming limit in case of multistage deformation. The tradition forming limit diagram (FLD) is useful for proportional and signal stage deformation, however, often it does not provide a satisfactory result in non-proportional, multistage deformation.

In my present work Experiments such as Uni-axial Tension test in Rolling, Transverse; A Diagonal direction of the sheet, Hole Expansion Ratio, Circular Cup Drawing and Forming Limit Diagram will be performed. The effect of Blank Holding Force and Punch displacement on subsequent deformation will be studied using Experimental, Numerical, and Simulation methods. Hill’s 48 yield criteria will be used to find the Anisotropy value. ABAQUS will be used for simulating these processes.

Keywords: Anisotropy, Formability, Simulative test, Simulation, ABAQUS.

1. Introduction

Sheet metal forming is a process of converting a flat sheet metal into the desired shape without defects. Formability is an ability of a sheet metal to be formed without failure. Sheet metal is one of the most important semi-finished products of the steel industry and sheet metal forming technology is, therefore, an important mechanical engineering field. Sheet Metal forming is a manufacturing process where a metal sheet is stretched, drawn or bent under force to give it desired shape. This process depends on numerous parameters like component geometry, material properties, tool designs and applied forces. Laboratory and workshop tryouts are often needed to determine a suitable combination of these parameters and obtain a successfully stamped product.

The demands required from the sheet metal processes are increasing with regard to tolerance of the finished part, light weight, complexity. To meet these requirements, a detailed knowledge about material properties, friction conditions and forming process is needed. This knowledge can only be obtained by using advanced theoretical and experimental engineering methods. To meet this demand, there is need to provide different tests in different rolling directions of sheet metal. To get an optimal direction of the sheet, while maintaining strength, formability and dent resistance is one of the objectives of every Steel manufacturer. The basic forming characteristics of sheet metal are to some extent indicated by simple intrinsic mechanical properties obtained from tensile tests in Rolling, Transverse, and Diagonal direction [1]. However, the tensile test does not simulate the complex forming modes (strain state) existing in a real stamping. It completely ignores the effect of processing variables like die-punch geometry, lubrication, punch speed, sheet surface finish, and tooling, on the forming behavior of the sheet metal. Hence, there is need of test which can assess material formability in actual press forming operation. Such tests are called as Simulative tests. Press forming operation is a complex interaction of processing variables. Simulative tests can be used for three purposes in sheet metal forming. Prediction of successful forming by given steel in a specific stamping is very close when made by the simulative test route. Effects of material properties and various process parameters can be studied without interaction from other forming modes. The results then are extrapolated to the more complex forming processes [2]. Simulative tests have axis symmetrical and simple shapes and thus help in verifying various mathematical models for predicting forming behavior. A typical industrial stamping is usually formed by a complex combination of bending, drawing and stretching mode. Some tests are single mode tests, while others are combinations of different modes.

Finite Element Method used for Sheet Metal Forming Simulation. The development of reliable analytical
procedures to predict the deformation and stress-strain field in sheet-metal forming makes it possible to improve the process. However, this development has encountered serious obstacles as geometric nonlinearity due to large deformation, material nonlinearity due to the plastic deformation, and kinematic nonlinearity due to the contact of sheet metal with the punch and the die along with friction at the contacting surfaces. The analytical methods have been useful in predicting the forming loads and overall geometry changes of deforming work pieces with an approximation. However, accurate determination of the effects of various process parameters on the detailed metal flow has become possible with the use of finite element methods. This method is sufficiently versatile to handle various geometries, materials and boundary conditions, hence widely used in the analysis of sheet metal forming. Finite element modules such as ABAQUS, PAMSTAM etc. were used to model the simulative test, which is now widely used in both automobile and steel industries.

2 Literature review

Comstock et al. [3] did Hole expansion in a variety of sheet steels. In this, the influence of the edge conditions on the hole expansion ratio according to the production method of the hole. The author developed an equation was proposed to predict the hole expansion ratio and a correlation between the hardening exponent and the hole expansion ratio for IF and austenitic-ferritic steels was developed. Toshihiko Kuwabara et al. [4] did Effect of anisotropic yield functions on the accuracy of hole expansion simulations. In this, compared biaxial tensile tests, hole expansion test and simulation results on the behavior of 780Mpa grade DP steel sheet to understand the effect of the anisotropic yield. M. Dunckelmeyer et al. [5] did Instrumented hole expansion test. He observed that hole expansion test was not influenced by the penetration speed, the clamping force and irregularities of the machine. Karellova et al. [6] did Influence of the edge conditions on the hole expansion property of dual-phase and complex-phase steels. He analyzed the influence of the edge conditions on the hole expansion property of dual-phase and complex-phase steels and observed that imperfections and damage introduced into the material in the vicinity of the hole have a detrimental influence on the hole expansion property. A Col and P. jousserand [7] did Mechanisms involved in the hole expansion test. He investigated the reasons for the high levels of strains observed in the whole expansion test compared to the conventional tensile test. C. Chiriac and G. Chen [8] did Local formability characterization of AHSS-digital camera based hole expansion test development. He investigated the influence of clamping force, the alignment of the specimen and penetration speed of the cone on the hole expansion ratio. The penetration speed and clamping force did not show any influence on HER, whereas the alignment of the specimen has an observable influence. Karellova et al. [9] did Hole Expansion of Dual-phase and Complex-phase AHSS steels—Effect of Edge Conditions. He found that complex-phase steel grade CP800 has higher HER than dual-phase (DP) for identical hole edge conditions, even though the tensile tests indicated opposite behavior. HER was found to be strongly related to steels microstructure and its constituents phases, especially the strength of the matrix and the contrast in hardness between softer and harder phases. Levy and Van Tyne [10] did Review of the Shearing Process for Sheet Steels and Its Effect on Sheared-Edge Stretching. In this, the depth of the shear-affected zone is less than the sheet thickness and is probably less than half of the sheet thickness. Fang et al. [11] did The Relationships between Tensile Properties and Hole Expansion Property of C-Mn Steels. He found that C-Mn steels with a high ratio of yield strength to ultimate tensile strength usually enhance the HER, while high carbon content is detrimental to HER. Chen et al. [12] did on the Stretch-Flange ability of High Mn TWIP Steels. He observed that HER of advanced high strength (HS) steel is influenced by material parameters such as normal anisotropy, strain hardening exponent, and strain rate sensitivity apart from microstructure and hole edge defect. Sugimoto et al. [13] did Stretch-Flangeability of a High-Strength TRIP Type Bainitic Sheet Steel. He found that the higher HER of the TRIP steel is due to the amount of retained austenite contained. The tool for prediction of deformations and cracks which might lead to the failure of the structure is an active research field. Such tools find extensive applications in industries such as automobile, aerospace, etc. where human safety is of utmost importance. One such tool that is extensively used in sheet metal industry to evaluate is Forming Limit diagram is mentioned on Metal forming—Mechanics and Metallurgy [14]. FLD was first conceptualized by Keeler and Co workers. Keeler et al [15] did Sheet metal forming and testing, in G.E. Dieter (Ed.), Workability Testing Techniques. FLD was first conceptualized by Keeler and Co workers. He also observed that the maximum local elongation was not enough to determine the possible straining rate of a sheet which compelled the author to establish the forming limit curve by plotting of the principal strains at fracture *σ*₁ and *σ*₂ on two axes. FLD has been widely used to optimize and correct problems in line production. The FLDs have enabled the prediction of which deformation can lead to the failure of the material for different strain paths and are considered an important tool in the dying process. In this process, grid circles are first etched into the sheet metal. The etched metal sheet is then stamped up to the failure. The etched circles now assume the shape of an ellipse and by measuring the dimensions of bigger and smaller axis the strain is calculated. The FLD is traced from the combination of the strains which lead to the failure. Erichsen, Swift, Nakazima [16] did Specimen preparation sheet metal marking. He observed that the few simulative tests used for the sheet metal formability evaluation. Erichsen test is used to determine the limit draw ratio. As the other one test simulates almost all the strain paths, they are mainly used to determine the forming limit diagram (FLD). Marciniak and Kuczynski [17] did limit strains in the processes of stretched forming sheet metal. He observed that the pioneers in the field of numerical prediction of FLD their model MK, takes the shape of an initial imperfection as a groove throughout the material which causes the surface to be weakened locally. Choi et al. [18] as well as Pishbin and Gillis [19] did Calculation of the forming limit diagram and Forming limit diagrams calculated using Hill’s nonquadratic yield criterion. Both have worked in another method known as JG. JG model is built on the assumption that strain occurs in three steps: first homogeneous strain up to the ultimate load; second strain concentration under constant load; third located necking with a sudden drop of the load. These steps along with material work hardening of contour conditions are mathematically represented to form an equation system which enables to describe the behavior of the metal during all the process of strain. Kwon et al. [20] did limit diagrams of zinc and zinc alloy coated steel sheets. In this, “located shear instability” criterion is used along with a yield criterion to obtain the FLD. The method assumes that only when the tension of the shear reaches a critical value, located shear will happen. On comparing the results agree with that of MK method, the model adopted by Know et al. is found to be more conservative. A.F. Graf, and W.F. Hosford [21] did Calculations of
forming limit diagrams for changing strain paths, Metall. They have used the Hill'93 criterion in the study of the effects of the properties of the material in the prediction of the FLCs, showing that the shape of the geometric place of the yield criterion has a big influence on the limit strains. Many researchers have investigated the formability of sheet metals in terms of the strain rate. In particular, they have investigated how the strain rate sensitivity affects the forming limits of sheet metals with regard to the necking and instability of sheets. L. Zhao et al. [22] did a theoretical and experimental investigation of limit strains in sheet metal forming. He found that Strain hardening exponent and the strain rate hardening exponent are found to have a huge influence on the limit strain, tensile instability and necking in sheet metals, with limit strain increasing with strain hardening and strain rate hardening rate.

3. Problem Formulation

Interstitial free (IF) steel is found to have very good ductility ability with low strength, compared to other grades of steel. Due to its superior ductility and formability of IF steel is found to be very good. Extra Deep Draw (EDD) steel has moderate ductile and strength properties. These steels are widely used in automobile industries. It is important to know the formability of these steel grades. In this work, IF and EDD steel supplied by Tata Steel has tested for their Mechanical properties using tensile tests in different rolling directions. Whole expansion ratio (HER) and cupping test also measured to determined stretch flange ability and draw ability characteristics respectively. Finally Forming limit diagram was drawn using ARGUS software to determine major and minor strain path at Drawing, biaxial and Plain Strain mode.

4. Materials and methods

4.1 Steel Grades

4.1.1 IF Steel:

IF Steel belongs to the category of ultra low carbon family in which the interstitial C and N are removed in the form of carbides and nitrides by suitable alloy additions are called IF steels. The 0.7mm thick IF Steel used in the present investigation was supplied by Tata Steel, Jamshedpur. It has high r-value and high strain hardening (n) coefficient. IF Steel has excellent formability and is suitable for larger deep drawing operations. Extra deep draw steels contain less than 0.05% of C and Mn up to about 0.2%.

4.1.2 EDD steel:

EDD sheets are produced by either batch or continuous annealing of cold-rolled sheet steels. EDD steels under studied were supplied by Tata Steel. The thickness of steel obtained was 0.7mm.

4.1.3 Tensile test sample Preparation:

Flow chart of sample preparation is given in above figure. The 50mm×50mm sample sheet collected from Tata Steel is thoroughly washed and the sample outline is marked along rolling, transverse and diagonal direction. The sample is cut using a vertical hacksaw, ALLCUT supplied by Hyderabad Allwyn metal works Ltd. The cut sample is straightened with the help of a C Clamp and then Milled in a Universal Horizontal Milling Machine (DoAll Contour 16). The sample is filed to remove the burr. The finished samples are then taken to the Universal testing Machine for Tensile tests. Sheet samples were collected and thoroughly washed and the sample outline is marked along rolling, transverse and diagonal directions. The rectangular sample is then cut using the vertical hacksaw, ALLCUT supplied by Hyderabad Allwyn Metal Works Ltd. The cut sample is then milled in a Universal horizontal Milling Machine (DoAll Contour 16). The sample failed to remove the burrs. The finished samples are then taken to the Universal Testing Machine for Tensile Tests. As per standards, the dimensions of the specimen have taken. Tests were performed on the machine Instron 5582. The crossed head speed was 10 mm/min and for strain measurements, a video extensometer was used.

4.2 ARGUS:

4.2.1. Image capturing step:

The original circular grid pattern is deformed to ellipse after forming. The sample is placed on a flat ground. Two axis markers are placed along the x and y axis (assumed) and square markers are placed at 4 corners. It is important to define and fix the position of grids with a particular of the frame of reference. This job is done by axis markers. The orientation of the grid is recognized by the square marker. The third set of markers is used to recognize the grids, which are not recognized and captured by the camera as shown in figure 1.

4.2.2 Material:

Extra Deep Draw Steel Interstitial Free Steel

Figure 1: FLD samples of 200mm length and decreasing width from 200mm to 25mm with decrement of 25 of IF and EDD Steel
4.3 Tensile Test of IF Steel

(i) Rolling Direction:

The tensile data for IF Steel in rolling direction are shown in Table 1.

Table 1: the tensile test of IF along rolling direction for RED-1, RED-2 and RED-3

| Sample No. | True stress at Yield (Mpa) | True strain at Maximum Load (%) | True stress at Break (Standard) (%) | True Straining Exponent at Peak Value | Plastic Strain Ratio at Value | Yield Value |
|------------|---------------------------|---------------------------------|-----------------------------------|--------------------------------------|-----------------------------|-------------|
| IF-1       | 454.64                    | 202.65                          | 13.64                             | 4.89                                 | 2.04                        | 1.23        |
| IF-2       | 448.62                    | 191.56                          | 20.98                             | 4.68                                 | 2.15                        | 1.23        |
| IF-3       | 148.82                    | 206.12                          | 27.54                             | 4.59                                 | 2.42                        | 1.62        |

The graph shows the comparison between true stress and true strain in rolling direction for IF steel are shown in figure 2.

(ii) Diagonal Direction:

The tensile data for IF Steel in diagonal Directions are shown in table 2.

Table 2: Tensile test of IF steel along diagonal direction for RED-1, RED-2 and RED-3

| Sample No. | True stress at Yield (Mpa) | True strain at Maximum Load (%) | True Stress at Break (Standard) (%) | True Straining Exponent at Peak Value | Plastic Strain Ratio at Value | Yield Value |
|------------|---------------------------|---------------------------------|-----------------------------------|--------------------------------------|-----------------------------|-------------|
| IF-1       | 153.35                    | 250.97                          | 27.71                             | 51.98                                | 0.244                       | 1.94        |
| IF-2       | 148.55                    | 288.73                          | 27.85                             | 52.64                                | 0.246                       | 1.69        |
| IF-3       | 174.47                    | 383.11                          | 29.02                             | 49.74                                | 0.236                       | 2.17        |

The comparison between true stress and true strain in diagonal direction for IF steel are shown in figure 3.

(iii) Transverse Direction:

The tensile data for IF Steel in transverse Directions are shown in table 3.

Table 3: Tensile test of IF steel along transverse direction for RED-1, RED-2 and RED-3

| Sample No. | True stress at Yield (Mpa) | True strain at Maximum Load (%) | True Stress at Break (Standard) (%) | True Straining Exponent at Peak Value | Plastic Strain Ratio at Value | Yield Value |
|------------|---------------------------|---------------------------------|-----------------------------------|--------------------------------------|-----------------------------|-------------|
| IF-1       | 138.15                    | 299.52                          | 16.17                             | 47.93                                | 2.217                       | 2.26        |
| IF-2       | 146.79                    | 290.66                          | 20.51                             | 50.52                                | 2.155                       | 2.39        |
| IF-3       | 151.99                    | 341.47                          | 27.11                             | 50.30                                | 2.252                       | 2.28        |

The comparison between true stress and true strain in transverse direction for IF steel are shown in figure 4.
4.4. Tensile test of EDD

(i) Rolling Direction:
The tensile data for EDD Steel in rolling Direction are shown in table 4.

**Table 4: Tensile test of EDD steel along rolling direction for RED-1, RED-2 and RED-3**

| Sample No. | Tensile stress at Yield (0.2%) (MPa) | Tensile strength at Maximum Load (MPa) | Elongation at Yield (%) | Elongation at Break (Standard) (%) | Stress hardening exponent n (Value) | Plastic Strain Rate at Value (Automatic) | Rate 1 (mm/min) |
|------------|-------------------------------------|----------------------------------------|------------------------|----------------------------------|-----------------------------------|----------------------------------------|---------------|
| RED-1      | 173.51                             | 580.75                                 | 20.88                  | 47.14                            | 0.316                             | 1.546                                  | 5             |
| RED-2      | 173.62                             | 586.97                                 | 26.67                  | 44.45                            | 0.322                             | 1.703                                  | 5             |
| RED-3      | 178.43                             | 586.65                                 | 27.31                  | 44.32                            | 0.326                             | 1.785                                  | 5             |

The comparison between true stress and true strain in rolling direction for EDD steel are shown in figure 5.

![Figure 5: Tensile test of EDD along rolling direction for RED-1, RED-2 and RED-3](image)

Figure 5: Tensile test of EDD along rolling direction for RED-1, RED-2 and RED-3

(ii) Diagonal Direction:
The tensile data for EDD Steel in diagonal Directions are shown in table 5.

**Table 5: Tensile test of EDD along diagonal direction For RED-1, RED-2 and RED-3**

| Sample No. | Tensile stress at Yield (0.2%) (MPa) | Tensile strength at Maximum Load (MPa) | Elongation at Yield (%) | Elongation at Break (Standard) (%) | Stress hardening exponent n (Value) | Plastic Strain Rate at Value (Automatic) | Rate 1 (mm/min) |
|------------|-------------------------------------|----------------------------------------|------------------------|----------------------------------|-----------------------------------|----------------------------------------|---------------|
| RED-1      | 170.37                             | 289.92                                 | 26.45                  | 46.96                            | 0.201                             | 2.845                                  | 5             |
| RED-2      | 174.51                             | 295.24                                 | 26.32                  | 48.08                            | 0.203                             | 2.828                                  | 5             |
| RED-3      | 172.66                             | 298.01                                 | 25.63                  | 44.44                            | 0.204                             | 2.820                                  | 5             |

The comparison between true stress and true strain in diagonal direction for EDD steel are shown in figure 6.

![Figure 6: The graph of tensile test of EDD along diagonal direction For RED-1, RED-2 and RED-3](image)

Figure 6: The graph of tensile test of EDD along diagonal direction For RED-1, RED-2 and RED-3

(iii) Transverse Direction:
The tensile data for EDD Steel in three transverse Directions are shown in table 6.

**Table 6: Tensile test of EDD steel along transverse direction for RED-1, RED-2 and RED-3**

| Sample No. | Tensile stress at Yield (0.2%) (MPa) | Tensile strength at Maximum Load (MPa) | Elongation at Yield (%) | Elongation at Break (Standard) (%) | Stress hardening exponent n (Value) | Plastic Strain Rate at Value (Automatic) | Rate 1 (mm/min) |
|------------|-------------------------------------|----------------------------------------|------------------------|----------------------------------|-----------------------------------|----------------------------------------|---------------|
| RED-1      | 178.23                             | 309.59                                 | 25.40                  | 40.36                            | 0.211                             | 1.595                                  | 5             |
| RED-2      | 198.74                             | 315.86                                 | 24.82                  | 42.63                            | 0.212                             | 1.571                                  | 5             |
| RED-3      | 178.70                             | 304.02                                 | 24.75                  | 45.89                            | 0.216                             | 1.487                                  | 5             |

The comparison between true stress and true strain in transverse direction for EDD steel are shown in figure 7.

![Figure 7: Tensile test of EDD along transverse direction for RED-1, RED-2 and RED-3](image)

Figure 7: Tensile test of EDD along transverse direction for RED-1, RED-2 and RED-3
The tensile Stress at yield offset 0.2% of IF was less as compare to EDD. Tensile stress at maximum load of IF was less as compare to EDD. Axial strain of IF was more than EDD. Tensile strain at break is more in case of IF than EDD. Strain hardening exponent of both grade of Steel was same. Plastic strain ratio of both the Steel is same. Rate of extension was 5 mm/sec. for both the samples.

5. Simulation of Model on ABAQUS:

5.1 HER:

Simulated punch load versus displacement data were matched for IF Steel as shown in Figure 8. A coefficient of friction among punch-blank, die-blank and blank holder-blank was 0.12 was found to be suitable for all calculation from simulation. Similar study was done for EDD Steel.

![Figure 8: Experimental and simulated punch load versus displacement data for hole expansion test](image)

Finite element simulation was used to understand the deformation modes associated with the hole expansion Ratio process. The present model accurately predict punch load versus displacement data for IF and EDD Steel. The finite element models of HER are shown in figure 9.

![Figure 9: the finite element result of HER](image)

5.2 Cupping Test:

Simulated punch load versus displacement data were matched for IF Steel as shown in Figure 10. A coefficient of friction among punch-blank, die-blank and blank holder-blank was 0.12 was found to be suitable for all calculation from simulation. Similar study was done for EDD Steel.

![Figure 10: Experimental and simulated punch load versus displacement data for Cupping test](image)

Finite element simulation was used to understand the deformation modes associated with the Cupping process. The present model accurately predict punch load versus displacement data for IF and EDD Steel. The finite element models of cupping test are shown in figure 11.

![Figure 11: the finite element result of cupping test](image)

5.3 FLD:

Simulated punch load versus displacement data were matched for IF Steel as shown in Figure 12. A coefficient of friction among punch-blank, die-blank and blank holder-blank was 0.12, 0.11, 0.09 was found to be suitable for all calculation from simulation. Similar study was done for EDD Steel.

![Figure 12: Experimental and simulated punch load versus displacement data for FLD](image)

Finite element simulation was used to understand the deformation modes associated with the Forming Limit Diagram analysis. The present model accurately predict punch load versus displacement data for IF and EDD Steel. The finite element models of FLD are shown in figure 13.
6. Conclusion

Without using a failure onset of necking can be accurately predicted from the simulation. Tensile test data results were used in the simulation, without considering the damage criterion. The results obtained by this FEM simulation accurately matched the result of Simulative tests experimental data. Hill’s 48 Yield criteria were used for simulation. Major strain and minor strain can be determined by feeding tensile results into the simulation, without any need of any Simulative tests. Using this model distinctive testing can avoid. In future, this simulation can be used to validate other grades of steel.

7. References

[1] Choi W, Gillis P.P, Jones S.E, 1989, “Calculation of the Forming Limit Diagrams”, Metall. Trans. A, Vol.20A, pp. 1975 – 1989.
[2] D. Banabic, 2000, “Formability of metallic materials: Plastic anisotropy”, Formability testing, Forming limits, Springer.
[3] R.J. Comstock, D.K. Scherer, R.D. Adamczyk, 2006, “Hole expansion in a variety of sheet steels”, Journal of Materials Engineering and Performance, 15(6), pp. 675-683.
[4] Toshihiko Kuwabara et, 2011, “Effect of anisotropic yield functions on the accuracy of hole expansion simulations”. Journal of Materials Engineering and Performance, pp. 475-481.
[5] M. Dunckelmeyer, 2009, “Instrumented hole expansion test”, Proceedings of International Doctoral Seminar, Smolenice Castle, Slovakia.
[6] A. Karelova, C. Krempaszky, E. Werner. T. Hebesberger, A. Pichler, 2007, “Influence of the edge conditions on the hole expansion property of dual-phase and complex-phase steels”. Symposium on Advanced High Strength and Other Speciality Sheet Steel Products for the Automotive Industry, pp. 159-169.
[7] A. Col, P. Jousserand. Sweden, 2008, “Mechanisms involved in the hole expansion test”. International Deep Draw Research Group, IDDRG 2008 International Conference, Olofström, pp. 197-205.
[8] C. Chiriac, G. Chen. Sweden, 2008, “Local formability characterization of AHSS-digital camera based hole expansion test development”. International Deep Draw Research Group, IDDRG 2008 International Conference, Olofström, pp. 81-91.
[9] A. Karelova, C. Krempaszky, E. Werner. P. Tsipouridis, T. Hebesberger, and T. Pichler, 2009, “Hole Expansion of Dual-phase and Complex-phase AHS Steels—Effect of Edge Conditions”, 80(1), pp 71–77
[10] B.S. Levy and C.I. Van Tyne, 2012, “Review of the Shearing Process for Sheet Steels and Its Effect on Sheared-Edge Stretching”, J. Mater. Eng. Perform, 21, pp. 1205–1213.
[11] X. Fang, Z. Fan, B. Ralph, P. Evans, and R. Underhill, 2003, “The Relationships Between Tensile Properties and Hole Expansion Property of C-Mn Steels”, J. Mater. Sci., 38, pp. 3877–3882.
[12] L. Chen, J. Kim, S.-K.Kim, K.-G.Chin, and B.C. De Cooman, 2010, “On theStretch-Flangibility of High Mn TWIP Steels”, Mater. Sci. Forum, pp. 278–281.
[13] K. Sugimoto, J. Sakaguchi, T. Iida, and T. Kashima, 2000, “Stretch-Flange ability of a High-Strength TRIP Type Bainitic Sheet Steel”, ISIJInt. 40(9), pp. 920–926.
[14] W.F. Hosford, R.M. Caddell, 1993, “Metal forming—Mechanics and Metallurgy”, 2nd ed., PTR Prentice-Hall, New Jersey.
[15] A.K. Gosh, S.S. Hecker, S.P. Keeler, 1984, “Sheet metal forming and testing”, American Society for Metal, Metals Park, pp. 133–195.
[16] Erichsen, Swift, Nakazima. 2014, “Specimen preparation: sheet metal marking”. ERICHSEN GmbH & Co. KG.
[17] Z. Marciniak, K. Kuczynski, 1967, “Limit strains in the processes of stretched forming sheet metal”, Int. J. Mech. Sci. pp. 609–620.
[18] W. Choi, P.P. Gillis, S.E. Jones, 1989, “Calculation of the forming limit diagram”, Metall. Trans. A 20A, pp. 1975–1987.
[19] H. Pishbin, P.P. Gillis, 1992, “Forming limit diagrams calculated using Hill’s non quadratic yield criterion”, Metall. Trans. A 23A, pp. 2817–2831.
[20] J.W. Kwon, D.N. Lee, I. Kim, 1994, “Forming limit diagrams of zinc and zinc alloy coated steel sheets”, Script. Metall. Mater, 31, pp. 613–618.
[21] A.F. Graf,W.F. Hosford,1993, “Calculations of forming limit diagrams for changing strain paths”, Metall. Trans. A 24A, pp. 2497–2501.
[22] L. Zhao, R. Sowerby, M.P. Sklad, 1996, “A theoretical and experimental investigation of limit strains in sheet metal forming”, Int. J. Mech. Sci. 38, pp. 307–1317