The effect of anisotropy on the intermediate and final form in deep drawing of SS304L, with high draw ratios: Experimentation and numerical simulation

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Abstract: High deep draw ratio of metal sheets is often required in industry to produce complex structural components and is considered to be problematic beyond a draw ratio of 1.7. In addition, anisotropy of material plays a great role in the final form of deep drawn products. In this research AISI SS304 L high draw ratio deep drawing (HDR) cups have been developed by using multiple intermediate annealing steps. The form of flange produced at each draw step is recorded. Numerical simulation of the process is carried out using ABAQUS Standard™. Accurate modelling of the process requires anisotropic parameters. Tensile tests at 0°, 15°, 30°, 45°, 60°, 75°, 90° to the rolling direction are carried out to determine the Lankford coefficients and hardening coefficients in each direction. The detailed material data obtained is then applied to simulate the HDR process. The forms recorded experimentally are compared with simulation results and conclusion is drawn as to the accuracy of the simulation.

Notations

- wo: Width of specimen before test
- wf: Width of specimen after test
- lo: Length of specimen before test
- lf: Length of specimen after test
- rx: Lankford’s r-value in rolling direction
- ry: Lankford’s r-value in transverse direction
- R22: Anisotropy coefficient in x-direction to simulate anisotropy in ABAQUS
- R33: Anisotropy coefficient in y-direction to simulate anisotropy in ABAQUS
- R12: Anisotropy coefficient in x-y plane to simulate anisotropy in ABAQUS
1. Introduction

A. S. Korhonen\[1\] devised a technique for estimating the maximum drawing force in the deep drawing of cylindrical cups. He approximated that at the limiting drawing ratio maximum force will act at the punch nose rounding and that there will be no contact between the sheet and the punch at the point of necking, so that frictional force cannot assist in carrying any drawing load. He proposed simple charts for determining the maximum drawing force as a function of anisotropy and tooling geometry. M. Ahmetoglu, et al. \[2\] found the wrinkling and fracture boundaries of aluminum alloy 2008-T4 to remove defects, increase part quality and rise the draw depth. They performed experiments on oval, oblong and rectangle specimens by varying the Blank Holding Force (BHF). They concluded that BHF as a function of time increases the formability and quality of final part. Xi Wang and Jian Cao \[3\] based on simplified flat or curved sheet models with approximate boundary conditions devised a modified energy approach utilizing energy equality and the effective dimensions of the region undergoing circumferential compression. Xi Wang and Jian Cao \[4\] devised a method is based on the wrinkling principle suggested by Cao and Boyce \[5\] for forecasting the buckling performance of sheet metal under normal limitation. They used a mixture of energy conservation and plastic bending theory. Their analysis provided the serious buckling stress and wavelength as affected by normal pressure. The results obtained were in excellent arrangement with those obtained from Cao and Boyce’s numerical method \[5\], and also matched well with the experimental outcomes of a square cup development. They also discussed that how wrinkling behavior is affected by material properties.

Anupam Agrawal, N. Venkata Reddy and P.M. Dixit \[6\] predicted the minimum blank holding pressure compulsory to evade wrinkling in the flange region during axisymmetric deep drawing procedure. They equated the energy accountable for wrinkling to that which overpowers the wrinkles. The model was verified by comparing with already published data. S. Han, M. Bruhis, and M. K. Jain \[7\] developed a new FE model for deep drawing and redrawing, which also accounted for the stiffness of working machine. a mathematical model to determine the limiting drawing ratio (LDR) of deep drawing and redrawing procedures was resulting based on the extension of an existing analytical model proposed by Leu \[8\] and Hill’s anisotropic criterion \[9\]. The consequences of the scientific model were validated by consistent experimental and FE simulation work in relationships of punch load and clamping force against punch displacement and thickness allocations along the product profile.

R. Padmanabhan, M.C. Oliveira, J.L. Alves and L.F. Menezes \[10\] worked on the effect of process parameters on the deep drawing of stainless steel. They used Taguchi method to recognize the relative effect of each process restriction. They found out that die radius has the highest effect on the deep drawing of stainless steel blank sheet followed by the effect of blank holder force and the friction coefficient. They also found out that blank holder force and local lubrication arrangement improves the superiority of the formed part. M. Kadkhodayan and F. Moayyedian \[11\] based on the Tresca yield criterion, bifurcation functional and Tresca yield criterion along with the assumption of perfectly plastic material developed a closed-form answer for the critical drawing stress. In their study they used nonlinear plastic stress field and the deformation theory of plasticity. For larger width of flanges they successfully predicted effect of a blankholder upon wrinkling and on the number of waves produced. It was also demonstrated that using large deflection theory has the same result as the using small deflection theory.

Wang Wu-rong, et.al. \[12\] worked on the limiting drawing ratio (LDR) and formability forecast of progressive high strength dual-phase steels (DP-AHSS). They conducted experiments to recognize the maximum blank diameter with onset crack, then simulated the same problem using three yielding models (Hill \[9\], Batlat\[13\] and Banabic \[14\]). The investigation showed that a Swift and Hockett–Sherby joint formula is in good contract with the flow curve of the tensile test and Batlat-89 yield model positively forecasts the beginning of shear crack of DP AHSS.

In the current research cups with high deep draw ratios (HDR) have been developed using multiple deep draw punches with intermediate annealing steps. Experimentations was done using customized die assembled on MTS 810 system to determine various parameters affecting the deep drawing process i.e. force applied, punch displacement and gripping pressure on sheet blank. Evolution of flange shape from circular to complex polygonal shape was also studied by recording the
flange shape after each step in pictorial form. Detailed material testing was done to determine plastic properties, strain hardening coefficients and Lankford’s r-values at 0°, 15°, 30°, 45°, 60°, 75°, 90° of sheet where 0° is rolling direction and 90° is transverse direction. This material model was used while defining numerical simulation model. Results obtained from numerical simulation were compared with actual experimentation, it was observed that due to good definition of numerical model it predicted the experimental trends very closely with some errors.

2. Experimentation

2.1. Materials

2.1.1. AISI D2
Die for hydroforming was manufactured using AISI D2. The chemical composition [15] of this material is shown in Table 1, and mechanical properties of AISI D2 [16] are shown in Table 2. The material was heat treated by using ASTM B661-12 [17].

| Component | C  | Si  | Mn  | Cr  | Mo  | V  | Ni  | Co  | Cu  |
|-----------|----|-----|-----|-----|-----|----|-----|-----|-----|
| Wt. %     | 1.55 | 0.3 | 0.4 | 11.8 | 0.8 | 0.8 | 0.3 | 1   | 0.25 |

| Density Kg/m3 | Young’s Modulus GPa | Poisson’s Ratio | Compressive Yield Strength MPa | Thermal Conductivity W/m.K | Specific Heat KJ/Kg.K |
|---------------|---------------------|----------------|--------------------------------|---------------------------|-----------------------|
| 7700          | 210                 | 0.3            | 2200                           | 20                        | 0.46                  |

2.2. AISI SS304
Chemical composition of AISI SS304 [15] is shown in Table 3 and mechanical properties of AISI SS304 [16] are shown in Table 4.

| Component | C  | Cr | Fe  | Mn  | Ni  | P  | S   | Si  |
|-----------|----|----|-----|-----|-----|----|-----|-----|
| Wt. %     | 0.08 | 18-20 | 66.3-74 | Max. 2 | 8-10.5 | 0.045 | 0.03 | Max. 1 |

| Density Kg/m3 | Poisson’s Ratio | Young’s Modulus GPa | Yield Strength MPa | UTS MPa | Rockwell Hardness |
|---------------|-----------------|---------------------|--------------------|----------|-------------------|
| 8000          | 0.3             | 200                 | 215                | 505      | 70                |

To determine detailed plasticity data tensile tests 0.5mm thick SS304L sheet were done using ASTM E8 Standard [18] at different deformation speeds. Results of these tests are shown in Figure 1. It can be observed that the material is highly stain rate dependent. At deformation speed of 0.48 mm/min, it shows the yield strength of 223 MPa, at deformation speeds of 4.8 mm/min and 48 mm/min, the material shows yield strength of 273 MPa and at speed of 480 mm/min it has very high value of yield strength which is close to 400 MPa. Hence it can be concluded that AISI SS304L shows greater strain hardening at higher strain rates, hence it should be deep drawn at relatively lower strain rates.
Commercially available rolled sheets show anisotropic behaviour while forming. To determine the Lankford $r$-values for anisotropy, specimens were prepared and tested according to the ASTM E517 Standard [19]. As for sheet only planar anisotropy is considered, specimens were cut in 3 directions which have been represented in Figure 2.

According to standard they were elongated 20% to their original length and the data shown in Table 5 was recorded for further calculations. Specimens before testing and after testing have been presented in Figure 3.

**Figure 1.** Stress Strain diagram for 0.5mm thick sheet at different deformation speeds

**Figure 2.** Extraction of 3 specimens for the test and determination of $r$-values according to ASTM E517 Standard
The r value is considered a measure of sheet metal draw ability, $\Delta r$ is measure of the tendency to form ears in the flange of deep drawn cylindrical parts in the direction of higher r values [19]. The results of these tests are discussed later.

3. Experimental setup
Die was designed for blank of 70mm diameter to get a deep draw ratio of 2.5 during deep drawing, and internal bulge was introduced to hydroform the final cup into a relatively complex shape. The schematics of the deep drawing process has been shown in Figure 4. Clamping rods, spring and flanges were used to incorporate load cell into the assembly, so that the gripping force on sheet blank could be estimated. Different modes of final assembly have been shown in Figure 5.

Before drawing, sheet was lubricated using graphite grease, and gripping pressure of 20kN was applied on the gripper to eliminate wrinkling, these gripping pressures were kept constant throughout the experiment. It was observed that the flange becomes hard due to excessive deformation radially and tangentially. The sheet was fully drawn into the die using multi step deep drawing with intermediate annealing steps. The process was conducted using force control technique to avoid the sheet from reaching the limiting force, which was 34kN in our case.

Die, grabber and punch were manufactured using AISI D2. After machining these parts were heat treated by following ASTM B661-12 [17], to make these parts hard enough so that they might not deform at very high pressures which were to be applied during the hydroforming process. External surface of punch and internal surface of grabber were ground to attain tight fit of hydraulic grade.
Figure 4. Schematics showing the basic deep drawing process

Figure 5. Final assembly of experimental setup for deep drawing and hydroforming (a) exploded view showing all components (b) sectioned view

Fully assembled die was mounted on MTS 810 system to operate the whole process in a controlled manner, and to get a detailed set of data which can be further processed to develop accurate relationships between above mentioned boundary conditions affecting the outcome of the process. We were able to set exact gripping force due to incorporated load cell into the assembly, and get force and displacement data from the LVDT and load cell of MTS 810 system. Analysis of data has been presented in results and discussion section.
4. Image processing

Commercially available metal sheets behave anisotropically when drawn into cups. This behaviour is due to the longer metal grain development in rolling direction and smaller metal grains in transverse direction. This anisotropic behaviour affects the final shape of part. In this research, we closely observed the experimental behaviour of material flow into the die cavity. Shape of flange after each step was recorded, using NIKON D600 with standard 55mm lens of f/5 aperture, at ISO-100, exposure time of 0.5 seconds and resolution of 300 dpi in horizontal/vertical directions, to produce a set of images as shown in Figure 6.

These images were then further processed using commercially available java 1.6.0_20 based code for image processing “Image J 1.47v” developed by National Institute of Health USA. The processed set of images is shown in Figure 7.
These images were then processed in MATLAB to trace boundaries. Centroids of each polygon could be selected manually or automatically. Manual selection was preferred as it produced better results. Radial distance of boundary from centroid after specific interval of angle was recorded and processed to get desired radial plots, which were then compared with the simulation results.

5. Finite element analysis

The detailed FE analysis of the procedure was carried out on ABAQUS Standard TM 6.12. The problem was simplified by only considering deformable sheet blank, rest all the parts including plunger, die and grabber were considered to be rigid. Detailed finite element analysis was performed on the final assembly of all the components as shown in Figure 8.

Figure 7. Processed images showing the evolution of flange shape after each step
Die, grabber and punch were modeled to be as 3D analytically rigid revolved shells as per actual drawing. While sheet blank was modeled to be as 3D deformable solid revolved part of 70mm diameter and of 0.5mm thickness. The blank was then sectioned to assign appropriate material properties and mesh to specific areas. Sectioned sheet blank has been shown in Figure 9.

Material properties of elastic modulus, poisson’s ratio and density were assigned to the sheet blank as shown in Table 4, while the plastic properties of SS304L were determined from tensile tests and were defined as shown in Figure 10.
Figure 10. Plastic properties of 0.5mm thick sheet of SS304L, 25°C and 48mm/min strain rate

Anisotropic material properties play a great role in the final shape of the formed part. To keep this effect under consideration during simulation standard anisotropic tests using ASTM E517 [19] were conducted for 0° (rolling direction), 45° (medial direction), 90° (transverse direction). Three tests in each direction were carried out and the results were averaged to minimize the error. Observation of these tests are shown in Table 5.

Table 5. Average change in respective length and width of specimens and their corresponding r-values in 3 directions

|                    | Thickness (t) (mm) | Length (l) (mm) | Lankford’s r-values |
|--------------------|-------------------|----------------|--------------------|
|                    | Initial (t₀) | Final (t₂) | Initial (l₀) | Final (l₂) |                      |
| Rolling (0°)       | 19.81          | 18.31        | 20              | 24              | 0.760165             |
| Medial (45°)       | 19.76          | 17.78        | 20              | 24              | 1.375956             |
| Transverse (90°)   | 19.76          | 18.19        | 20              | 24              | 0.8317542            |

(1) was used to calculate the r-values using the data obtained from tests. Calculated r-values at 0°, 45° and 90° are shown in Table 5.

\[
 r = \left( \frac{\ln \frac{w_f}{w_0}}{\ln \frac{l_f}{l_0}} \right) 
\]

(1)

These r-values were converted to anisotropic coefficients of ABAQUS using (2), (3) and (4) which have been discussed in software documentation respectively.

\[
 R_{22} = \frac{r_y(r_x+1)}{\sqrt{r_x(r_y+1)}} 
\]

(2)

\[
 R_{33} = \frac{r_y(r_x+1)}{\sqrt{r_x+r_y}} 
\]

(3)

\[
 R_{12} = \frac{3r_y(r_x+1)}{\sqrt{(2r_{45}+1)(r_x+r_y)}} 
\]

(4)
Values of R11, R13 and R23 have been kept 1 because of the planar anisotropy. Above mentioned values of R22, R33 and R12 are applicable when the sheet lies in plane 2-3. The values will be defined in the respective boxes if the plane of sheet changes. All the corresponding values of constants have been presented in Table 6.

| Coefficient | R11 | R22 | R33 | R12 | R13 | R23 |
|-------------|-----|-----|-----|-----|-----|-----|
| Value       | 1   | 1.023 | 0.959 | 1   | 1   | 0.858 |

In simulation, all parts were assembled together using coaxial position constraints and using displacement command. To exactly simulate the actual process 8 dynamic explicit steps considering nonlinear geometry were defined with consecutive annealing steps, to soften the material after each punch. Isothermal frictionless surface to surface contacts were assumed between die-sheet pair and grabber-sheet pair, while rough surface contact was defined for punch-sheet pair. Die, grabber and punch were constrained to be rigid along their respective reference points. While defining the boundary conditions, die and grabber were fixed initially to grip the sheet, and punch was displaced in each step to comply with the actual experimental data.

The sheet was meshed using approximate global size of 0.0014 with total 10832 nodes and 7989 elements. 7875 3D explicit linear hexahedral C3D8R (8-node linear brick, reduced integration, hourglass control) elements and 114 3D explicit linear wedge C3D6 (6-node linear triangular prism) elements were defined to homogeneously mesh the blank. Global material orientation was defined using global coordinates of the part. Final meshed sheet blank is shown in Figure 11.

Figure 11. Final mesh of sheet blank

Figure 12 shows the shape of flange after each deep drawing step as predicted by numerical simulation model. It can clearly be observed that numerical simulation adapted the anisotropic deformation in flange and predicted the evolution of flange shape from circular to complex polygonal shape till the end of experiment. Detailed results obtained from numerical simulation and its comparison with experimental data have been discussed later.
6. Results and discussion

High draw ratio deep drawing (HDR) can be a useful tool to manufacture relatively complex parts, which are difficult to manufacture otherwise. Simulation model with detailed material properties, directional strain hardening coefficients and Lankford's r-values predicts the experimental parameters and geometric outcomes. It was observed during experimentation that it is impossible to achieve draw ratios of 2.46 in single punch, hence multiple deep drawing steps with intermediate annealing steps to remove residual stresses in the flange and soften the material are necessary.

It was observed that anisotropic hardening properties of sheet play a great role in the development of final shape of finished product. To predict the actual shape of flange with the help of simulation, detailed material model should be defined, tensile tests in which each specimen was elongated 20% were done. Figure 13 shows the graph of strain hardening coefficients at different directions. 0° is the rolling direction of sheet while 90° is the transverse direction of sheet. Strain
The hardening coefficient (n) for our sheet varies from 0.258 to 0.267. It is interesting to note that material is soft at 0° (rolling direction) and shows constant increase in hardening till 60° (medial direction) after which the hardening coefficient decreases until we reach 90° (transverse direction). As discussed in previous section, tests were conducted for first and third quadrant only at 0°, 15°, 30°, 45°, 60°, 75°, 90°, 180°, 195°, 210°, 225°, 240°, 255°, 270° (filled markers) and the results were extrapolated for 360° circle (hollow markers) assuming symmetric strain hardening coefficients for second and fourth quadrant.

![Figure 13. Strain hardening coefficients at respective orientation of commercially available SS304L sheet](image)

It was observed during experimentation that it is impossible to achieve draw ratios of 2.46 in single punch. During deep drawing the flange deforms and hence becomes hard and stops flowing into the die cavity. Necking at wall of deep drawn cup occurs and eventually the part fails. Figure 14 shows the force displacement curve of one step deep drawing process during which the part fails. Similar curve of failure for cup wall was obtained multiple times during experimentation. Depth of drawing is directly proportional to the force applied. It can be observed that specifically for our case, maximum or limiting drawing force (LDF) which can be applied during deep drawing is 34kN. In one step deep drawing the part fails at 16mm depth.

Similar problem was simulated in ABAQUS Standard as discussed previously, and the simulation results are shown in Figure 14. Simulation model predicted the limiting drawing force to be 25kN with 13mm depth of drawing. While comparing both curves it can be seen that the overall trend of both curves is very similar, yet numerical simulation model under predicts the force and displacement when compared with experimental values.

![Figure 14. Comparison of experimentation and simulation results for tearing of sheet wall during one step deep drawing](image)
As single step HDR is not possible, it was carried out using multiple deep drawing steps with intermediate localized annealing of flange to remove residual stresses and soften the flange before the wall reached the limiting force which it can carry. Figure 15 shows the force displacement curves for multi-step deep drawing process. Complete process was carried out in 8 steps. Process was conducted using force control technique and limiting force was set to be 28kN. As the force reached the limiting value after each step, part was removed from the die, flange was quick annealed using oxy-acetylene torch. 2nd and 6th punch of experimentation show less deep drawing for exactly the same amount of force applied in all steps, it is because of relatively higher gripping pressures in these 2 steps. There is a drop of force in 8th step which shows that the part has been fully drawn into the die. In Figure 15 experimental results (hollow makers) have been compared with the simulation results (solid markers) as well. It can be seen that simulation model predicts the trends of force displacements curves very closely, with the fact that initially the predicted force is highest and it gradually decreases with decrease in flange area and in final step the prediction of force is lower than the actual value. Ideally it should be the case when the contacts are frictionless.

![Figure 15. Comparison of experimentation and simulation results for multi-step deep drawing with intermediate annealing](image)

Flange shape after each punch was recorded as shown in Figure 6 and was compared with the flange shape predicted by the simulation model which has been discussed in the previous section. Comparison of results for 1st, 4th and last steps are shown in Figure 16-18 correspondingly. Simulation model predicts greater flow of material into the die cavity, it is because of the frictionless model which has been assumed during simulation.

![Figure 16. Comparison of flange shapes from experimentation and simulation after 1st step](image)
Error between flange shapes obtained from experimentation and those predicted by simulation was calculated at 0°, 45° and 90°. Error plot after each step has been shown in Figure 19. Initially the blank is circular with radius of 35mm in experimentation and simulation, still there is up to 4% error, it might come due to the processing of flange shape during edge detection in MATLAB. It can be observed from the figure that there is an increasing trend in error up till 6th punch, which then decrease in the next punch, it is because simulation predicts greater material flow into the die cavity during each step and the error tends to increase.

It can be observed that error in all directions follows same trends, but at 45° there is least error (max 12%) in the prediction of flange shape, at 90° the error in prediction of flange shape is intermediate (max 17%) and maximum error is seen at 0° orientation of flange (max 22%).
7. Conclusion
Effect of anisotropy on the final shape of deep drawn parts has been investigated. Material was tested to determine detailed material data and Lankford’s anisotropic coefficients, which was further used to develop detailed numerical simulation model to exactly predict the final shape of the flange. Detailed material model with Lankford’s anisotropic coefficients was used to define detailed numerical simulation model to precisely predict the force-deformation curve and final shape of flange after each deep draw step. Experimental results were compared with numerical simulation.

By observing Lankford’s r-values in Table 5, it can be concluded that rolled material is most ductile in rolling direction (0°), 8.4% less ductile in transverse direction (90°) and 44.7% less ductile in medial direction (45°). Which is the exact trend of material while flowing into the die cavity. Deformation is maximum in rolling direction and least in medial direction as shown in Figure 7. It was observed that it is impossible to attain HDR of 2.46 in single step. Excessive deformation of flange hardens the flange which hinders its flow into the die cavity and the cup wall fails as depicted by force-deformation curve of single punch in Figure 14. It is recommended to anneal the flange of cup as soon as the limiting value of force is achieved which in our case was 28 kN.

Impossibility of attaining HDR of 2.46 for 0.5mm thick sheet of AISI SS304 was also predicted by numerical simulation model with an average error of 14% as shown in Figure 14. Numerical simulation predicts on average 7% to 12% more material flow into the die cavity than actual experimental results because of the frictionless model defined, the detailed error plot in 3 directions for each step has been presented in Figure 19.

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9. References
[1] Korhonen, A.S., Drawing force in deep drawing of cylindrical cup with flat-nosed punch. Journal of Engineering for Industry, 1982. 104: p. 29
[2] Ahmetoglu, M., et al., Control of Blank Holder Force to Eliminate Wrinkling and Fracture in Deep-Drawing Rectangular Parts. CIRP Annals - Manufacturing Technology, 1995. 44(1): p. 247-250
[3] Wang, X. and J. Cao, *On the prediction of side-wall wrinkling in sheet metal forming processes*. International Journal of Mechanical Sciences, 2000. 42(12): p. 2369-2394

[4] Wang, X. and J. Cao, *An Analytical Prediction of Flange Wrinkling in Sheet Metal Forming*. Journal of Manufacturing Processes, 2000. 2(2): p. 100-107

[5] Cao, J. and M. Boyce, *Wrinkling behavior of rectangular plates under lateral constraint*. International Journal of Solids and Structures, 1997. 34(2): p. 153-176

[6] Agrawal, A., N.V. Reddy, and P.M. Dixit, *Determination of optimum process parameters for wrinkle free products in deep drawing process*. Journal of Materials Processing Technology, 2007. 191(1–3): p. 51-54

[7] Han, S., M. Bruhis, and M. Jain. *Some Considerations In Modeling Axisymmetric Deep Drawing And Redrawing Process And LDR Prediction*. in AIP Conference Proceedings. 2007

[8] Leu, D.-K., *The limiting drawing ratio for plastic instability of the cup-drawing process*. Journal of Materials Processing Technology, 1998. 86(1): p. 168-176

[9] Hill, R., *The mathematical theory of plasticity*. Vol. 11. 1998: Oxford university press

[10] Padmanabhan, R., et al., *Influence of process parameters on the deep drawing of stainless steel*. Finite Elements in Analysis and Design, 2007. 43(14): p. 1062-1067

[11] Saxena, R.K. and P.M. Dixit, *Prediction of flange wrinkling in deep drawing process using bifurcation criterion*. Journal of Manufacturing Processes, 2010. 12(1): p. 19-29.

[12] Wu-rong, W., et al., *The limit drawing ratio and formability prediction of advanced high strength dual-phase steels*. Materials & Design, 2011. 32(6): p. 3320-3327.

[13] Barlat, F. and K. Lian, *Plastic behavior and stretchability of sheet metals. Part I: A yield function for orthotropic sheets under plane stress conditions*. International Journal of Plasticity, 1989. 5(1): p. 51-66

[14] Banabic, D., et al., *An improved analytical description of orthotropy in metallic sheets*. International Journal of Plasticity, 2005. 21(3): p. 493-512

[15] Volume, A.H., *I: Properties and Selection: Irons, Steels, and High-Performance Alloys*. ASM International, 1990

[16] Handbook, M., *Desk edition*. ASM, Metals Park, 1985

[17] ASTM, *B661-12 Standard Practice for Heat Treatment of Magnesium Alloys*. ASTM Standards, 2012

[18] E8, A., *Standard test methods for tensile testing of metallic materials*. Annual book of ASTM standards, 1997. 3.

[19] Standard, A., *E517-00. ASTM Standard Annual Book Vol. 0.3, 2000. 1*