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Analysis of Effective Parameters in Design of CNG Pressure Vessels

Iman Rostamsowlat[1], Hamid Madani nasab[2]

Abstract— **The mass production of natural gas pressure vessels is needed to be carefully examined concerning formation stages and the effective parameters on the production stages of the vessels .Since pressure vessels should be produced seamlessly, the conventional method for building vessels metal core include the use of an initial blank and performing deep drawing formation, redrawing, ironing and finally rotational forming for vessels dome and throat. In this paper a review of the history of production and the manufacturing method is presented. Then, finite element method is used for simulation of initial stages of forming the CNG vessel core. The simulation of production process consists of the cold deep drawing, cold redrawing and finally two steps of ironing the vessel walls (without considering hot spinning in order to close the vessel dome). A stage of stress releasing is performed at the end of each stage of forming. The required force for forming and also the change occurred in the blank thickness is examined in this study. The results of simulation done by other researchers were compared with the finding of this study. The comparison showed a good level of agreement between the obtained results. These results help the designers to design better.**

Index Terms— **CNG Pressure vessel, Deep drawing, Ironing, Redrawing, Stress releasing.**

I. Introduction

The use of compressed natural gas is rapidly increasing in the world. Therefore, there is an increasing national need for the production of CNG vessel is a complex, costly and time-consuming process, so that only a few developed industrial countries have been widely investing on the CNG vessel production. The production process of CNG vessel is too costly due to the need for accurate and sensitive machinery, expensive raw materials such as different kind of composite fibers, production technologies for initial forming to multi layer composite walls and finally different tests done on the vessel such as quality control test in different stages of production including ultrasonic test, hardness test, volume control, the required quality control tests done on composite vessel such as controlling resin viscosity or fibers length, fibers drawing, damage tolerance tests, environmental tests, life cycle tests and many others. The use of CNG as a fuel for automobiles began for the first time in a large scale in 1950 and 1960 in Russia and Italy.

The first vessels were heavy steel vessels produced various national-industrial specification. Until 1970, with making the new regulations in Italy, made it necessary to produce light steel vessels. The substitution of the other fuels by natural gas began in a large seal in North America from 1980. The light vessels were made of metal priming wrapped with glass fibers to be used in space applications and were available in industrial markets in 1977. In 1982, the vessels made of aluminum priming covered with glass fibers were used extensively. The manufactures applied these processes to produce lighter vessels by manufacturing steel priming covered by fiberglass which were produced in 1985 for the first time. In order to reduce the vessels weight, many manufactures developed complex composite projects and used plastic or metal priming to produce CNG vessels. In late 1980's, practical CNG vessels with reinforced plastic priming were used practically in Sweden, Russia, and French. Following the development of standards of CNG vessel production in North America, relatively thin aluminum priming, reinforced with plastic priming covered by fiberglass and carbon were produced and sent to the market.

CNG vessels are usually produced from raw materials in the form of the sheets, pipes, and bars. So using producing CNG vessels in three different shapes require different production process initial forming of raw materials will take the maximum volume of the production process. In order to produce steel or aluminum CNG vessels, first of all, aluminum or steel sheet will be chosen. The size of the initial blank should be chose so that, the minimal waste be possible depending on the size and requirements of the design parts. After preparing the sheets, stress releasing heat treatment will be done on them. Then the wrapped sheets will be flattened for cutting operation. The sheets will be cut in circular forms and desired size so that they bear the least amount of stress and possible cracks. After cutting the sheets, they will be imposed to oiling cycling to prevent the possible damage at the next stages. Then they will be exposed to cold deep drawing to give them a glass shape.

Lubricating the sheets before cutting them reduces the friction and facilitates the drawing operation. The vessels go under stress releasing after cold drawing operation and they will be put in oiling cycle. This makes the next cold redressing, softening, and stress releasing to be performed better. Then the vessels are redrawn to form the vessels, final diameter. When all these stages finished, the vessels are ironed in order for the walls to reach the desired width. In this stage, the deformations caused by foundry or rolling are partially removed. When the circular part of the vessel is

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1. Iman Rostamsowlat is with the Department of Mechanical Engineering, Islamic Azad University, Shiraz Branch, Iran. (corresponding author to provide phone: +98-9173310402; e-mail: iman.rostamsowlat@gmail.com)
2. Hamid Madani nasab is with Department of Mechanical Engineering, Shiraz University, Iran. (e-mail: hm_860898@yahoo.com)

ready, the walls are examined by ultra sonic test to be assured that they have the same width. In order to form pipe of the vessel, the hot spinning process is used. After this stage, the ironing of the vessel pipe and vessel core forming process is finished. Then the vessels are cooled down quickly heated up to increase vessels hardness and their resistance against any possible shock and releasing the residual stress resulting from forming operations. When the vessels are being formed and heated, some waste materials such as oxides will be appeared in and outside of the walls. To clean such waste materials, the vessels are bombarded by metal bars. Then the hardness test is done on the vessels and they are eye-examined to detect any appearance defect.

Afterwards, the final operation including cleaning and winding will be performed on the pipe. Then, the vessels are tested by ultrasonic to discover any possible defects. In doing so, the vessel surface should be cleaned by removing oils, oxides and contaminations. In order to make the vessels stronger, they are covered by composite fibers. The precision used in wrapping the fibers quickly and consistently is one of the principle process of the wrapping process. The process makes it possible for designers; make the vessels stronger by applying precise mechanical characteristics on the right places. It also allows the designers to improve thermal resistance and the stiffness of the used materials. This means that the engineers have the ability to change the variables in order to achieve the characteristics requested by the customers. The wrapping machine is a computer digital control machine having a highly efficient automated system, so that it can be started to work only in a few minutes. The application of this machine is not only limited to circular vessels. Any possible shape can be fiber-wrapped by the machine. It is also possible to wrap resin matrix and backed fibers in the room temperature and also in a kiln with a control thermal profile, depending on the resin matrix used for wrapping operation. The diameter and the centrifuge of the axis are exactly controlled to maintained final composite concentric by keeping on the composite interface with machine components. In order to start the wrapping operation, dry fiber poppets are adjusted so that a certain stress occurs in fibers. The amount of the fibers drawing can affect composite resistance and hardness parameters. The fibers are passed through resin pool and covered by resin.

In the next stage, the fibers are drawn and widened to make ready to be wrapped. When the fibers come out of resin pool, they are wrapped on the CNG vessel by wrapping machine. Depending on the different kinds of vessels, the wrapping can be done in rotational, axial, screw (or crossing) forms or a combination these forms. After being wrapped, the vessels come out of the wrapping machine and heat treatment is done on them. When matrix resin is being heated, it has a direct influence on the performance of the vessels composite structure. The time and heating temperature are controlled to optimize the composite performance. This action is done by electronic controlling system to keep the temperature of the boiler at the required level to insure that the composite structure has attained the determined properties. After the heating treatment is finished, the vessels are taken out of the boiler to be packed. The results of the above process are production of the vessels with a low weight but with a high level of efficiency. [1-3]

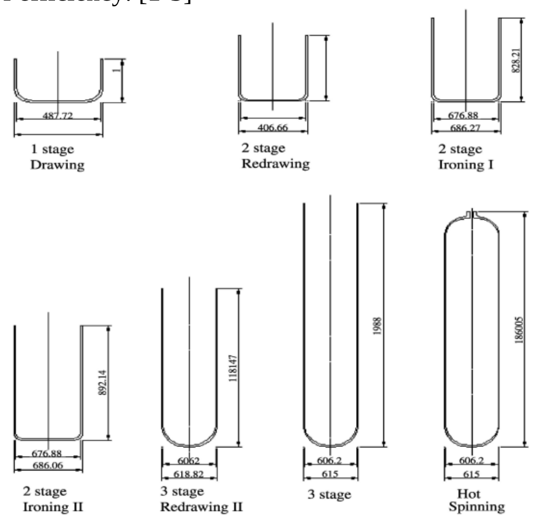

Fig1.Primary stages of the steel core forming a CNG vessel [2]

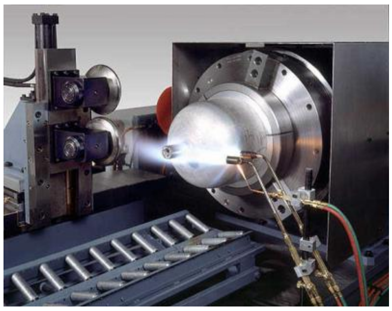
Fig2.Heat rotational forming (spinning) of the CNG dome [1]

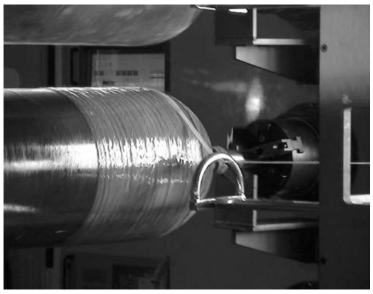
Fig3.Wrapping composite priming around the CNG vessel resin [1]

Deep drawing process is used to produce various products such as hollow cylindrical containers or the panels with complicated surfaces that used in automobiles industries.[4] The first simulation of the process was applied by Woo on a flat die based on the finite difference method for a axisymmetric parts.[5] Hrivank and Sobotova [7] Date and Padmanabhan [8] have investigated the effect of various parameters on deep drawing of the metal sheets. These parameters were the size of the grains, metal blank thickness, metal hardness and the rate of strain. Yossifon and Tirosh [9] compared experimental and theoretical methods to investigate the effects of hardness, anisotropy, and friction coefficient on the final thickness of produced blanks. Thiruvarudchelvan and Loh used a set of optimized devices to reduce friction and increase the allowed amount of drawing.

Research also investigated deep drawing process without using blank holders such as conic dies. The focus of research has been mainly on parameters such as variations in drawing

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force, wrinkling in the conic dies and geometric modification of drawing conic dies and tractrix dies. The access to high drawing ratio requires using redrawing process. This process was investigated by various researchers. The ironing is a key operation in order to obtain uniform wall thickness and larger height. The earliest research about this process was done for computing strains and ironing force by the elementary plasticity method. Analyses have been implemented by the homogeneous work method, lower bound method upper bound method and finite element method [6].

II. Simulation

The primary results of this simulation make it possible for researchers to reduce the trial and error stages and preproduction costs. The simulation also allows researchers to examine the effect of different parameters on the production process. Various parameters can be verified in each stage of vessels production process. These parameters are the quality of material flow, maximum level of required force, the distribution of strain-stress forces, effects of dies geometry, etc.

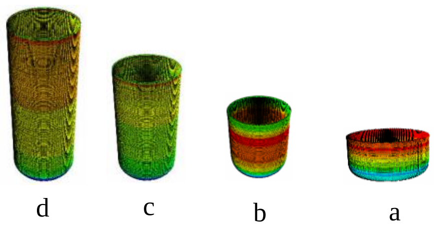

Fig4. Manufacturing stages: **a**) cold deep drawing b) cold redrawing c) first ironing d) second ironing [6]

The ABAQUS/EXPLICIT code is used to simulate all process. The Explicit solver is used frequently, because it is capable of analyzing high velocity dynamic problems, large deformation problems and large interfaces. In all of the analyses, the punch, the die and the blank holder have been considered as rigid and the blank as solid deformable [6]. Because the force, boundary conditions, and the geometry model are symmetric, for meshing we used CAX4R element that are axisymmetric. Six elements were used in the blank thickness direction and 575 elements were employed in the blank radius direction. After the simulation of the deep drawing process, the deformed model which was undergone annealing stress releasing was employed along with two other anneal stress releasing processes to perform continuous redrawing and ironing processes. The first stress releasing process was used after cold redrawing, while the others were used after ironing in the first stage.

Figure 5 shows a cross-section of a CNG vessel with its related dimensions [6]. The minimum wall thickness cannot be less than 5 millimeters after two ironing stages. The vessel volume is 137 liters with ellipsoidal end. This liner is manufactured from 6061-O aluminum blank with initial thickness of 12mm and, 1150mm in diameter. The mechanical properties of the used materials are shown in Table1 [6, 10]. Figure 7 shows work hardening curve behavior of the material [6]. The bulge test curve was used in the analysis as it is more representative of the material behavior in an axisymmetric forming process such as deep drawing, redrawing and ironing. In addition, the curve provides a wider range of strains for the actual stress-strain curve. Therefore, it was more suitable for numerical simulations.

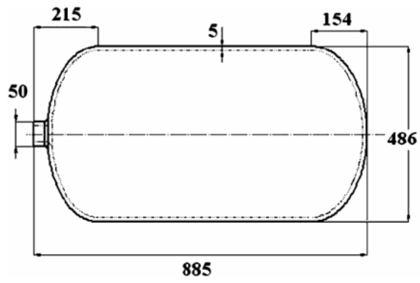

Fig5.Geometrical properties of the CNG vessel [6]

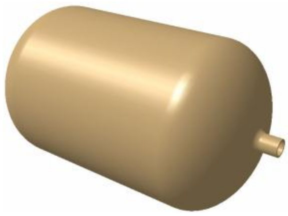

Fig6. 3D Model of the Vessel

Table1. Mechanical properties of AL 6061-O

σ_y (MPa)	E (GPa)	ν	σ_u (MPa)	ρ (Kg/m^3)
55.2	68.9	0.33	124	2700

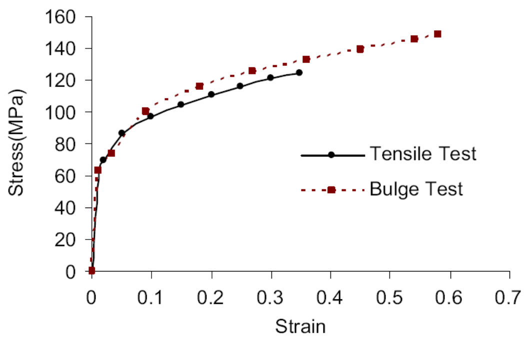

Fig7. Stress-strain curves resulted from tensile test and bulge test [6]

In order to determine the highest drawing ratio, several simulations of the process have been carried out with different drawing ratios. In these simulations, the edge radius of punch was 60 mm, the edge radius of the matrix was 80 mm and the amount of clearance was equal to 16.8 mm. The friction coefficient for the punch and the blank interfaces is 0.1 and for the matrix, blank holder, and the blank is 0.028[6]. The blank holder force is 90 KN at cold deep drawing stage. And finally after performing several simulations, the minimum drawing ratio at cold deep drawing was calculated 1.7. Therefore the ratio of the blank initial diameter to the punch diameter is equal to 1.7.

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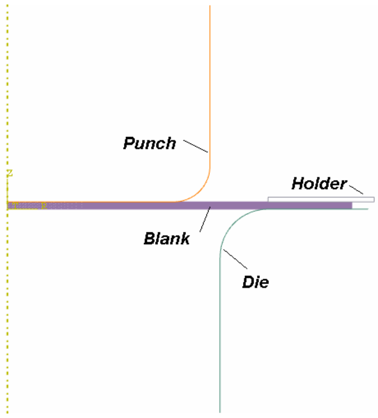

Fig8. Axisymmetric model for simulation of cold deep drawing

Figure 9 shows the force curve based on the punch displacement used for forming the vessel at cold deep drawing. As the figure shows, the maximum force obtained by the simulation is 1487.75 KN. The force increases in the curve due to performing initial bending and overcoming the friction force. As the punch move forward, the force is fixed due to the initial increase. The reason is that the force gets fixed due to the nature of the middle forming stages. In fact, the decrease in the blank surface located under the blank holder which leads to a decrease in the blank holder force compared to the total drawing force causes an increase in the drawing force and therefore, the previous decrease will be compensated. The result is that the drawing force is almost fixed at the distance of 220 mm in the punch stroke. The force decreases gradually when the blank is removed under the blank holder. The decrease will continue when the drawing operations ends at 380 mm if the punch stroke.

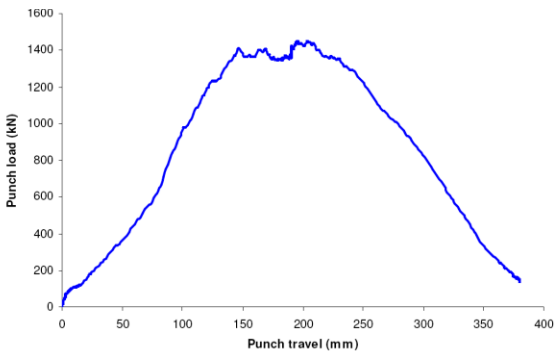

Fig9. Force-displacement curve of the punch in drawing stage (drawing ratio 1.7)

Figure 10 shows the changes occurs in the blank thickness when the deep cold drawing is performed. As it can be seen, there is a considerable amount of agreement between the result of simulations obtained in other studies [6] and this study.

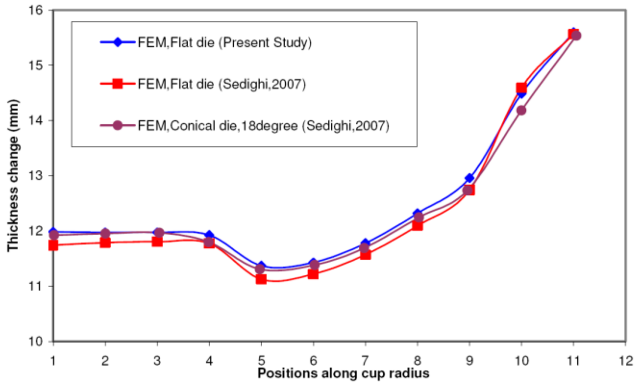

Fig10.Simulation result of changing blank thickness at the end of cold deep drawing

At the next stage, in order to carry out the CNG vessel cold redrawing, the produced capacity in the cold deep drawing stage with the height of 324 mm and interior diameter of 676.5 mm (with drawing ratio 1.7) was used as the primary model. An anneal stress releasing process was done on the container to eliminate all the stresses and strains produced in the cold deep drawing. All the residual stresses and strains are eliminated in this model and the deformed meshes produced in the previous stage are remained on the model. In order to obtain the vessel final diameter, the final drawing ratio was considered 1.41 to achieve the diameter equal to 486 mm in cold redrawing stage [6]. Friction coefficients between the interfaces are the same as the friction coefficient in previous stage. The blank holder force is 92 KN which shows an increase 2 KN comparison to cold deep drawing stage. This increase is due to a relative decrease of blank thickness n deep drawing stage and also a longer stroke in comparison to cold deep drawing which causes the blank has a longer interface with wrinkling [11].

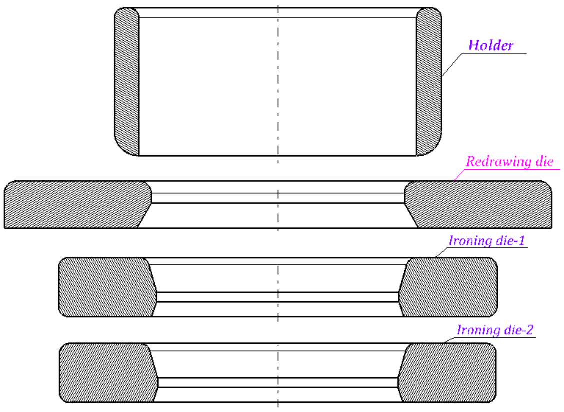

Fig11.schematic model of the redrawing and ironing dies

Figure 12 shows the force curve based on the punch displacement. If we compare this figure with figure 9, it becomes evident that the amount of cold redrawing force has increased due to an increase in the punch stroke, blank holder force, a decrease in the blank thickness, and finally a decrease in matrix diameter from 80 mm to 25.2 mm. The maximum force of drawing was 1487.75 KN in cold deep drawing which amounted to 2000 KN in cold redrawing stage. The blank thickness is 17.52 mm in cold redrawing stage which

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increase the redrawing force when the vessel edge is passing under the blank holder in the punch stroke of 500 mm.

In order to level the vessel wall thickness and achieve the desired thickness, two stages of ironing were simulated on the vessels walls. This process can be simulated with the deep drawing or redrawing stages or it can be carried out after this two stages. In order to obtain the final thickness, one or several stages of ironing are usually carried out. Depending on the amount of strain absorbed in each stage, the part undergoes anneal stress releasing heat treatment between each stage of ironing. The strain ironing factor will obtained through the following formulae, where t_o is the blank thickness and t_l is the thickness after the first ironing process.

$$E_i=(t_0/t_l) \quad (1)$$

$$E_{ii}=E_{i1}*E_{i2}*E_{i3}*\ldots*E_{in} \rightarrow t_0/t_n = (t_0/t_1)*(t_1/t_2)*\ldots*(t_{n-1}/t_n) \quad (2)$$

The amount of strain factor for different materials is given in the standard table and the decrease in the maximum thickness before each stage of heat retreatment can be calculated according to the table. The same friction conditions were regarded for simulating ironing process. A stage of anneal stress releasing was carried out between two stages of ironing. The maximum thickness of the blank was 17.52 mm in cold redrawing stage for the present simulation. The ironing strain factor was calculated using formula 1 and the wall's final thickness was considered 5 mm.(E=17.52/5) that friction coefficient and the maximum decrease of the wall thickness and the amount of allowed strain for each stage of ironing was measured according to the two previous ironing stages. The minimum wall thickness in the first die amounted to 8.76 mm after removing the vessel from the die. Concerning the maximum blank thickness is 17.52 mm, the amount of decrease in the first die is 50% and ironing factor for the first die is LIR=17.52/8.76 =2

In the second die, the blank thickness amounts to 5 mm. Consequently the amount of decrease and ironing factor for the second die are 42.92% and LIR=8.76 / 5 =1.752

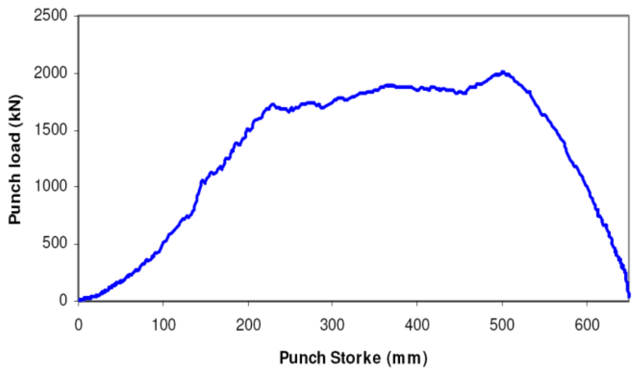

Fig12. Force-displacement curve of the punch in cold redrawing

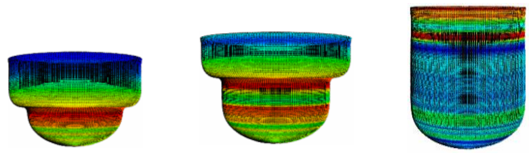

Fig13. Cold redrawing stages of CNG

Table2.Comoarison between deep drawing and redrawing

operation	Cold deep drawing	Cold redrawing
Holder Force (KN)	90	92
Drawing ratio	1.7	1.41
Clearance (mm)	16.8	18
Die radius (mm)	80	25.2
Max punch force (KN)	1487.75	2000
Blank thickness Min (mm)	11.4623	10.513
Blank Thickness Max(mm)	15.7	17.52
Final vessel height(mm)	323.738	631.755

Concerning the data shown in Table 3 and those related to simulation of redrawing and ironing in the first and second stages, the force curve is shown in figure16 based on the punch displacement in the vessel forming stages. The curve consists of three parts. The first part is related to cold redrawing stage. When the cold redrawing treatment finishes, the force gets zero which is in fact due to performing anneal stress releasing stage. After the anneal stages is performed, the punch keeps forward its movement and enters the ironing die of the first stage. Therefore, as the punch stroke increase, as the results the force also increases. Since the blank thickness is not the same in all points, it is drawn at the cold redrawing stage which increases the blank thickness. This increase along with the further downward movement of the blank and the blank transmission of the first die to level the blank thickness causes the force to increase progressively.

Table3.Comparison of ironing properties

Operation	First ironing	Second ironing
Thickness strain factor	2	1.751
Minimum of wall thickness(mm)	8.76	5
Final height of vessel(mm)	845.42	1376.21
Thickness decrease (%)	50	42.92

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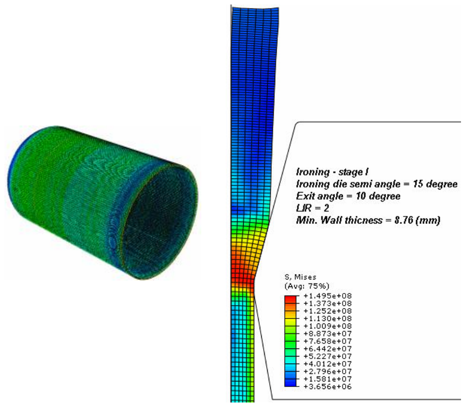

Fig14. After first ironing

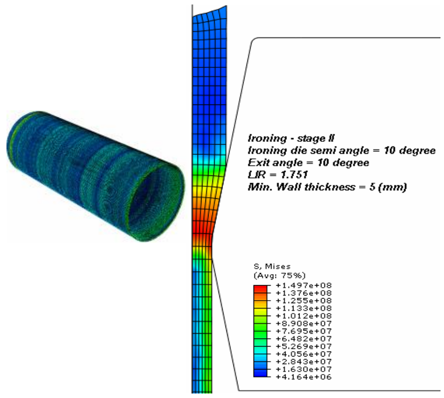

Fig15. After second ironing

When the blank passed through the first stage die edge and force reach its maximum amount in this stage, the punch force decreases to zero which is related to the second anneal treatment. After second annealing was performed, the punch moves downward and the vessel enters the second ironing stage and, therefore, the force increase again. Since the vessel thickness is the same in all points due to the first stage ironing, the force remains fixed and stable.

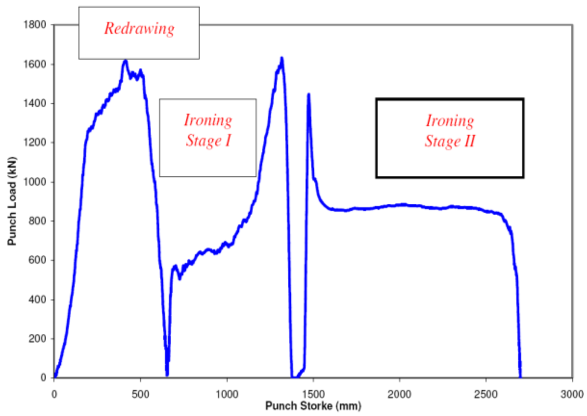

Fig16. Force-displacement curve in redrawing an ironing of the first and second stages

In order to investigate the changes occur in the blank thickness, a defined route is used based on figure 17. The changes in the blank thickness in 24 points of this rout will be recorded. These points begin from central blank point and end in blank external points. In figure 18, a comparison of blank thickness changes in cold deep drawing, cold redrawing, and ironing stages of vessel wall has been shown. As it can be seen the wall thickness is not the same in deep drawing and cold redrawing stages.

After performing two stages of ironing, the vessel wall thickness becomes the same which can be observed when compared with the vessel thickness in drawing and redrawing stages. In redrawing and ironing of the first and second stages, the thickness changes in figure 18 having the lable No.18 are very small. In fact positional changes and thickness reductions are happened in the interface between the punch and the die after cold redrawing is done in the ironing stage. This limitation is due to the existence of the amount of clearance less than the blank thickness. Therefore no force is imposed on the bottom of the vessel and the thickness in this area remains under changed and stable.

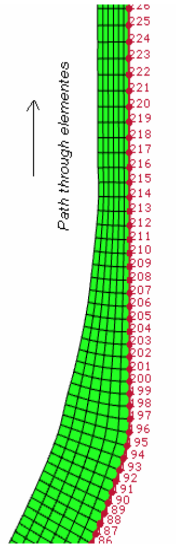

Fig17. Defined direction for studying of wall thickness

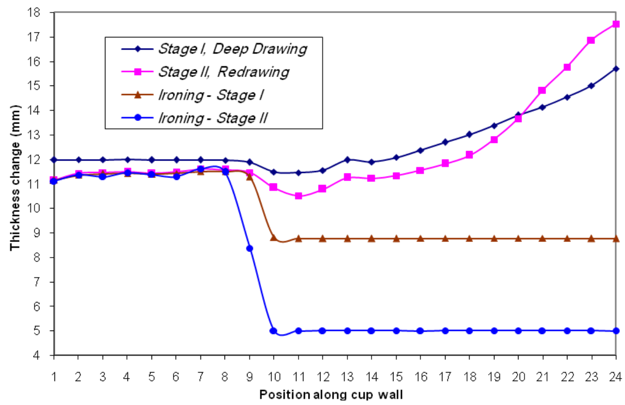

Fig18. Comparison of wall thickness in different stage of forming

III. Conclusion

In order to discover manufacturing stages and effective parameters on the forming process of the aluminum CNG vessel, this study simulated cold deep drawing, cold redrawing, and ironing stages done on the aluminum vessel wall by using finite element. The primary findings and analyses made it possible for the designers to decrease trial and error stages and preproduction costs and to investigate the effective parameters on the process. Different parameters can be studied in different stages of the manufacturing process of the vessel, including the quality of the material flow, the maximum required force, the distribution of the

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stress-strain force, and geometrical effects of dies. The forming process was simulated as follows:

- Cold deep drawing process
- Doing stress releasing annealing
- Transmission of the changed and annealed model in cold deep drawing to the redrawing die and doing cold redrawing
- Stress releasing annealing process
- First ironing
- Stress releasing annealing process
- Second ironing

The results of cold redrawing simulations in this study indicated that the maximum of the cold redrawing force is increased as the result of increase of punch stroke; the amount of more hardness in the punch stroke; an increase in the blank holder force; reduction in the blank thickness and also a reduction in die radius from 80mm to 25.2mm. The maximum amount of drawing force was 1487.75 KN in cold deep drawing which amounted to around 2000KN in cold redrawing process. The blank thickness also amounted to 17.52mm in cold redrawing which increased the redrawing force when the vessel is passing under the blank holder in the course of 500mm.

In order to obtain a wall thickness of 5mm, two stages of ironing were preformed along with an anneal stress releasing stage. The results of the simulation indicated that since the wall thickness was not the same in cold drawing stage and an increase in vessel thickness in the high part of the wall, the punch moved more downwardly and the vessel passed the die in the first stage which was accompanied by a stable thickness, these factors, altogether, increased the force progressively. When the vessel passed the first stage die and increased the force to its maximum level, the punch force decreased to zero level which was related to the second anneal stress releasing. After performing the second anneal, the punch moves downward and the vessel with a stable thickness in all points enters the second ironing die, therefore, an increase will be observed in the force. The force will remain stable in this stage, since the wall thickness is stable due to the first ironing stage. The results of the simulations also indicated that the wall thickness is not the same in deep drawing and cold drawing forming stages and the sameness of wall thickness can be observed if compared with deep drawing and redrawing process. After performing cold redrawing in the two stages of ironing, the changes occurred on the bottom of the vessel in figure 18, point labeled 8, are so trivial that can be ignored. In fact, after performing cold redrawing in ironing stages, since the amount of clearance is not so great, deformation and thickness reduction are done locally in the interfaces between the punch where the walls and the dies meet. Therefore, no force is applied at the vessel bottom to reduce its thickness. Therefore, the vessel bottom thickness remains fixed and stable until the end of the forming stage.

References

[1] C. Lorentzen. (1994). Networks [Online]. Available: http://www.MJCENGINEERINGANDTECHNOLOGY .com/ pressure_vessels/index.html

[2] J.C. Choi · Chul Kim · S.Y. Jung."Development of an automated design system of a CNG composite vessel using a steel liner manufactured using the DDI process". Int J Adv Manuf Technol, 2004, pp. 781-788.

[3] Vardga, L., Nagy, A., Kovacs, A., "Design of CNG tank made of Aluminum and Reinforced Plastic, "Composites, Vol.26, Issue 6, 1995, pp. 457-463.

[4] S.j. Allen, S.M. Mahdavian, "The effect of lubrication on die expansion during the deep drawing of axisymmetrical steel cups", Journal OF Material Processing Technology, 199, 2008, pp. 102-107.

[5] Woo DM (1964) Analyses of cup drawing process. J Mech Eng Sci, pp. 116–131.

[6] M. Sedighi & M. Rasti. "An investigation on manufacturing process parameters of CNG pressure vessels". Int J Adv Manuf Technol. DOI 10.1007/s00170-007-1139-0.

[7] A. Hrivnak, L. Sobotova, The influence of the deformation aging and the conditions of stress on the properties of the deep drawing steel sheet, J. Mater. Process. Technol, 34, 1992, pp. 425-430.

[8] P.P. Date, K.A. Padmanabhan, on the prediction of the forming limit diagram of sheet metals, Int. J. Mech. Sci, Vol. 34, No 5, 1992, pp. 363-374.

[9] S. Yossifon, J. Tirosh, On the dimensional accuracy of deep drawing products by hydroforming processes, Int. J. Mech. Sci, Vol 34, No4, 1991, pp. 279-295

[10] S. Thiruvarudchelvan, N.H. Loh, Drawing of cylindrical and hemispherical cups using an improved tooling for friction-actuated blank holding, J. Mater. Process. Technol,Vol 37, 1993, pp. 267-280.

[11] Jaebok NAM and Kyung Seop HAN. "Finite Element Analysis of deep Drawing and Ironing Process in the Steel D&I Canmaking". ISIJ.

[12] ABAQUS Version 6.7, Documentation, ABAQUS Analysis User's Manual, 2007.

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