THEORETICAL AND EXPERIMENTAL STUDY OF THE EFFECT OF SHEET THICKNESS OF ALUMINUM 1435 ON THE FINAL PRODUCT QUALITY AND STRESS DISTRIBUTION IN SPINNING SHEET METAL FORMING

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ABSTRACT :

Spinning sheet metal forming (SSMF) has demonstrated a great potential to form a wide range of industrial products which have an axially symmetric shape. This process produces a part with a good surface finish and high mechanical properties by using simple tools. In this study, the deformation mechanics were investigated by using two approaches, theoretical and experimental. The theoretical part included finite element models of cylindrical cups of Aluminum1435 using single roller passes and Finite Element code (ANSYS 15) were used to simulate the forming process and analysis the results theoretically. The effect sheet thickness on the final product quality, stress distribution were studied. The experimental study focused on the analysis of the shape accuracy produced by single pass metal spinning. The numerical results were obtained in this study revealing that, failure by fracture is a predominant when a sheet with 1mm thickness is used, while failure by wrinkling was observed when a sheet with 2 mm thickness was used, the product with 3mm thickness showed no defects. The experimental work included design and manufacturing of the forming tools can be fitted on the tool post of lathe after some modifications. The results of the thickness variation along the cup wall was measured and compared with that obtained numerically. The compared results showed a good agreement between them and the error percentage did not exceed 5.95%.

KEYWORDS: spinning, forming, sheet thickness, numerical simulation.

دراسة نظرية وعملية لتأثير سمك الصفيحة الألمنيوم 1435 على جودة المنتج النهائية وتوزيع الاجهادات عند تشكيل الصفائح المعدنية بالرحو

الخلاصة :

اثبت تشكيل الصفائح المعدنية بالرحو إمكانات كبيرة لتشكيل مجموعة واسعة من المنتجات الصناعية التي لها شكل متماثل محوريا. تنتج هذه العملية جزء ذو انهاء سطحي جيد والخواص الميكانيكية عالية باستخدام أدوات بسيطة. في هذه الدراسة تم التحقيق في ميكانيكيه التشوه باستخدام نهجين نظري وعملي. الجزء النظري تضمن نماذج العناصر المحددة للكؤوس الأسطوانية للألمنيوم 1435 باستخدام ممرات الرولة الأحادية وتم استخدام برنامج خاص بتقنية العناصر المحددة (ANSYS15) لمحاكاة عملية التشكيل وتحليل النتائج نظريا. تمت دراسة تأثير سمك العينة على جودة المنتج النهائية وتوزيع الاجهادات .ركزت الدراسة العملية على تحليل دقة الشكل الناتج بالرحو المعدني باستخدام المسار الواحد . كشفت النتائج العددية التي تم الحصول عليها في هذه الدراسة أن الفشل بالكسر هو السائد عند استخدام عينه سمكها 1mm ، في حين لوحظ ان الفشل بالتجاعيد عند استخدام عينه سمكها 2mm، المنتج مع سمك3mm لا يظهر عيوب. تضمن العمل التجريبي تصميم وتصنيع الات التشكيل والتي يمكن استخدامها على مقلمه المخرطة بعد اجراء بعض التعديلات. وقد تم قياس اختلاف السمك على طول جدارالكأس ومقارنتها مع تلك التي تم الحصول عليها عدديا .أظهرت نتائج المقارنة تقارب جيد بينها و نسبة خطأ لا تتجاوز 5.95٪.

1- INTRODUCTION :

SSMF is one of the metal forming operations, where a flat metal blank is formed by a roller which gradually forces the blank on the mandrel, to form the final shape of the product. Through the spinning process, the blank is clamped between the mandrel and tail stock, these three components rotate synchronously at a predetermined spindle speed as shown in **Fig.1**. [Runge 1994]. [Liu 2002] obtained the distributions of radial, hoop and thickness stresses of a conventional draw spinning in the first pass of the process under three types of roller race curves (straight lines, involute curves and quadratic curves) with an Elasto Plastic Finite Element Method. [Kleiner2002] selected possible input factors in their factorial experiments in order to identify the effects of key process parameters on the wrinkling failure in the spinning. These factors included the thickness of the blank and the axial feed of the roller tool. [Xia 2005] studied one path spinning of mild steel and pure aluminum cups experimentally. Forming conditions considered in their research included the thickness which was found to be important parameters affecting the spinning force, nominal thickness strain and material formability. [Sebastiani, 2007] presented Finite Element Analysis by means of the explicit code LS-DYNA. They used the mild steel (DC04) as circular blank. They concluded that the compressive stresses in the roller-facing and tensile stresses in the mandrel-facing surface. [Long and Hamilton2008] proposed the simulation of the forming of a cylindrical spun part by the single pass of a roller using FE dynamic explicit formulations. The results show that the non-uniformly distributed radial and hoop strains have a decisive effect on the variation of the thickness strain. [Essa and Hartley 2010] used the design of experiments (DOE) approach for generating experimental plan and conducted numerical simulation of the cylindrical cup. They assessed the results using the ANOVA technique to identify the most critical working parameters. They observed that the feed rate and roller nose radius were the most critical variables affecting ability of forming without wrinkling, also the initial sheet diameter, whilst important, had less effect and friction coefficient had no observable effect upon the process formability. [Hamilton and Long 2010] studied the material deformation mechanism and typical cases of material failure in conventional metal spinning. The development of explicit FE simulation models of a spun cylindrical part by a single-pass of the roller was reported. They observed necking around the filleted mandrel edge and thickening towards the part opening. The results show that wrinkling defects have been demonstrated at higher feed rates, although these effects may be exaggerated by the use of shell elements. [Wang 2010] carried out a one-pass spinning experiment with three factors varying at two levels by applying the Taguchi method. The experimental results also showed that using higher feed rates and low spindle speeds it resulted in a smaller reduction of wall thickness. [Wang and Long 2011] designed four different roller path profiles (linear, convex, concave and combined convex and concave). They studied numerically the effects of these roller paths on tool forces and part wall thickness in conventional metal spinning. The results showed that the concave path produces highest tool forces among these four roller path profiles and higher reductions of wall thickness of the product. Using the convex roller path, assisted in maintaining the original wall thickness unchanged. [Wang and Long 2013] proposed tool compensation technique in multiple roller passes design in conventional spinning. They applied Taguchi method and analyzed the effects of material type, feed ratio on the dimensional variations of the spun parts. They used finite element simulation to investigate the variations of tool forces and wall thickness High feed ratios can help to maintain the original wall thickness unchanged, but cracking failures may occur if a larger feed ratio was applied. Comparing with aluminum, mild steel has a better ability to stand cracking failures in the conventional spinning process. They observed that the axial force is the highest and the tangential force is the lowest and the wall thickness of the work piece decreases gradually after each forward roller pass. The thinnest zone on the work piece shifted from the bottom to the opening of the spun cup, while the spinning process progressed. [Lin 2015] proposed three different patterns of deformation allocation for curvilinear generatrix parts, including equal max deformation (EMD), equal arc length (EAL), and equal axial distance (EAD). They developed a 3D elastic-plastic finite element model to investigate the effects of deformation allocation on forming quality. This paper focused on studying the effect of blank thickness on the SSMF process in term stress distribution, thickness variation and wrinkling suppression.

2- STRESSES IN THE CONVENTIONAL SPINNING PROCESS :

Through the conventional spinning process, a local plastic deformation zone is created at the roller contact area. The stress forms in this zone depends on the roller feeding direction. In the forward pass (the roller feeds in the direction of the edge of the blank of sheet metal), tensile radial stresses and compressive tangential stresses are induced, as shown in **Fig.2a**. The tensile radial stresses lead to a material movement to the edge of the blank producing thinning of the blank, which is balanced by the thickening effects of the compressive tangential stresses, keeping a nearly constant thickness. In the backward pass (the roller feeds in the direction of the mandrel), though, the material builds up in front of the roller, producing compressive radial stresses and compressive tangential stresses, as shown in **Fig.2b** [Runge 1994].

3- STRESSES DISTRIBUTION :

The spinning procedure is very similar to deep drawing process according to the tools at the press. The process is carried out in one pass from circular plain preparing parts. For full analyzing of stress state at the spinning it is needed to divide the work piece into several changed zones. As shown in **Fig.3** at which are occurred different schemes of stress. The stress state is treated as flat at the element wreath, where it is considered that the forming of material is acted by the absence of normal stress (σ_Z) =0. This stress state is different in according to radial stress (σ_R) positive and normal stress in the tangent direction is negative (σ_T). The method of common solution of plasticity conditions is used for an analysis of stress in the element wreath in the form [Lazarevic 1983]:

$$\sigma_R - \sigma_T = \pm\beta k \qquad (1)$$

Where

σ_R= radial stress.

σ_T= tangential stress.

β = lode coefficient (1-1.55).

K = number of parameters.

And the balance equation is [Lazarevic 1983]:

$$\rho \frac{d_{\sigma_R}}{d\rho} + \sigma_R - \sigma_T = 0 \quad (2)$$

Where

ρ= radius inside of intervals ($r_1 \leq \rho \leq R_o$).

r_1 = radius of the mandrel.

R_0 = radius of blank of sheet metal.

From equations (1) and (2), we get the equation (3)

$$\rho \frac{d_{\sigma_R}}{d\rho} + \beta k = 0 \quad (3)$$

To solve the equation (3), boundary conditions ($\rho = R_S$, σ_r=0) are applied, we get radial stressed component at the element wreath as shown in equation (4).

$$\sigma_R = \beta . k_{sr} \ln \frac{R_S}{\rho} \quad (4)$$

Where

k_{sr} = the average value of specific flow stress.

R_S = the immediate value outside wreath radius of the cylinder (from r_1 to R_0).

From equation (4) and equation (1), we get

$$\sigma_T = \beta k_{sr} \left[\ln \frac{R_s}{\rho} - 1 \right] \quad (5)$$

The maximum axial stress is defined as [Lazarevic 1983]:

$$\sigma_{Z_{max}} = \left[1.1 k_{sr} \ln \frac{R_S}{r_1} + k_{sr} \frac{s_0}{2\rho_w + s_0} \right] (1 + 1.6\mu) \quad (6)$$

Where

s_0 = Initial thickness of blank

μ = The coefficient of friction

$$R_S = \frac{1}{2} \sqrt{(D_0^2 - 4 d_{1sr} [h + 0.57(\rho_w + R + s_0)])}$$

D_O = Original diameter of the blank

Where maximum axial stress ($\sigma_{Z_{max}}$) Obtained by h = 0.

4- FINITE ELEMENT MODELING:

In this paper, a commercial FE code (ANSYS 15) is used to simulate the spinning sheet metal forming operation. The material of sheet metal is aluminum alloy 1435. The mechanical properties of this material in experimental aspect are the elastic modulus of elasticity E = 69.500GPa, Poisson's ratio v=0.33, yield strength σ_y=130MPa and tangent modulus E_t=0.1GPa. Two Coulomb frictional coefficients have been assigned to two contact pairs of tools and blank: mandrel-blank 0.2 and roller-blank 0.02 [Razavi 2005]. The parts of the model in the simulation process are shown in **Fig. (4)** . The tool set (mandrel and forming roller) was modeled as rigid bodies. In the present study the elements used to simulate the blank is **SHELL 181**, contact elements is **CONTA174** and target elements are **TARGE170**. The blank diameter is 180mm. Mapped meshing is applied to discretize the plate material.

The best number of elements is (2660) element as it is shown in **Fig. (5)**. SSM forming processes under the large displacement static condition have been simulated. The load in the current study is applied by using the solution processor with load step options and then start the finite element solution. The load is defined by applying of zero all degrees of freedom at the contact line between the holder and sheet as the first load step, applying of roller travel in z - direction by distance 120mm and rotating about the z-axis as feed ratio as second load step and finally rotating about the z-axis by inertia then and finally angler velocity by global as a third load step.

5-THE EFFECT OF BLANK THICKNESS:

To investigate the effect of blank thickness on SSMF process, three different blank thickness, i.e. (1,2,3mm) were used. The feed ratio 0.71mm/rev and spindle speed 200rpm. Through the forming process, failure by cracking is observed with 1mm thickness of the blank, while failure by wrinkling is observed with 2mm thickness of the blank, while no failure is observed in the blank with 3mm in thickness. A global cylindrical coordinate system has been used to demonstrate the output of deformation and stress values. The radial direction is defined in line with the radial axis of the mandrel, while the tangential direction is in the path perpendicular to the radial axis and the axial axis of the mandrel. **Fig. (6)** and **Fig. (7)** shows the deformation in z-direction along the wall of the cup for with (2 and 3mm) thickness respectively. **Fig. (8)** to **Fig. (19)** show the nodal solution of the tangential stress, radial stress, axial stress and Von- Mises stress distribution along the wall of the cup with blank thickness (1, 2, 3mm). From these figures, it can be seen that the entire material is plastically deformed, the maximum value of Von-Mises stress on Aluminum cup is 0.321GPa, these values exceed the yield stresses. The distribution of Von- Mises stress reveals a reasonably uniform level for the entire of the deformed wall of the cup, but with some variations, especially on the inner surface of the wall towards the open end. It can be seen that sheet thickness has an important effect in the deformation process, where the maximum plastic deformation that takes place near the round corner of the mandrel (cup bottom) results from the maximum axial force. After that, the force decreases as necking occurs at the corner of the mandrel under large axial tensile stresses. If the sheet thickness is unable to support these large axial tensile stresses, circumferential cracking and fracture at the cup bottom are expected. **Fig. (20)** shows a typical wall thickness variation in which the part of the base of the cup which was hold between the mandrel and blank holder is almost constant, while there is local thinning around the mandrel corner and slight thickening near the open end. Additionally, no wrinkling can be observed.

5. EXPERIMENTAL WORK :

5.1. Testing the Work Material :

The tensile specimens were machined by a CNC milling machine and then grounded to the final size using different sand papers with different particle size. Tensile specimen dimensions shown in **Fig. (21)** were selected according to the ASTM standard A370 (the ISO specification). Uniaxial tension tests were carried out using the WDW model (200) with maximum load capacity 200 KN that is available at Babylon University- Collage of

Engineering Materials as shown in **Fig. (22)**. The specimens were loaded till fracture occurs. Tensile test was carried out at a crosshead speed (0.5mm/min).

5.2 Manufacturing of the Rig:

Spinning tests were carried out on a general-purpose center lathe after it was temporarily modified to work as a semi-automatic spinning machine. The values of spindle speed on the lathe were (31, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 600, 800, 1000, 1250,1600 rpm) and feed ratio (0.04, 0.05, 0.063, 0.08, 0.1, 0.125, 0.16, 0.18, 0.23, 0.28, 0.35,0.45, 0.56, 0.71mm/rev) as shown in **Fig. (23)**. The rig for spinning forming process was composed of the mandrel, blank holder, shaft, base and forming roller. In this work, 180mm diameter of the blank is selected due to the limitation of space of the available test machine used in the present work. The mandrel plays a very important role in giving the shape of the final product. The mandrel used for the experiment is made of steel (St 37) and consist of two cylindrical parts, the first part attached with a headstock of lath from the left side. The second part of the mandrel is attached to the other side of the first part by the cylindrical shaft which has a radius 40mm and length15mm and consist a small hole which has a radius 7.5mm and depth 20mm to assemble with a blank holder. The blank holder is used to attach the blank with the mandrel by a small pin from the side and with the tail stock of the lathe from the other side by a small hole. The forming roller which is the vital part of the forming rig were designed according to the reference (Xia 2005, Liu 2007, Essa 2009). 0The forming roller contains two ball bearings (6308NSE) which allow the forming roller to roll freely during the spinning process. High-strength steel (St-37) was used as a forming roller material The shaft which is used to carry the forming roller is especially designed to press fit the ball bearing to give the smooth rotation to forming roller. The base is an important part which is used to carry the shaft and the forming roller. The base contains five large holes with same diameter and depth to fix the base on the tool post and to control the location of the roller with respect to the blank. Also, there is a four small threaded holes used to fix the shaft that carrying the forming roller by the large hole on side view. The blank contains on the hole in the center with 15mm diameter for attaching**. Fig. (24)** shown the mandrel with two parts, plate and blank holder. **Fig. (25)** represented the assembled the roller with shaft with the base and finally **Fig. (26**)shows assembled rig parts .

6- THE FORMING PROCESS :

The forming process was conducted after loading the blank to the machine and fix it with the aid of blank holder by moving the tail stock of the lathe. After that the forming was done by moving the roller (tool post) displacement in the Z-direction (120mm) to create complete stroke for sheet forming with a predefined feed ratio (0.71mm/rev) and the running speed of the spindle (200rpm) (according to numerical results). The blank is (180,3 mm) diameter and thickness aluminum 1435 respectively. The SSMF during the forming process was spanned by using lathe model (500) with maximum spindle speed (1600 rpm) and a maximum feed ratio (0.71 mm/rev) in the university of Babylon -mechanical department. In the spinning sheet metal forming process, the sheet metal will be subjected to changed strains of stretching, bending and ironing. The new dimensions will result, the product defect are generated such as wrinkling as can be shown in **Fig. (27)**. Wrinkling is a particular defect in SSMF, which is resulted by compressive tangential stresses in the flange region near the local forming area do not completely recover to tensile tangential stresses after leaving roller contact. To measure the product thickness variation along the depth of the cup, the product was divided in two parts by using reciprocating saw, the cup before and after measuring the thickness as shown in **Fig. (28)**. Micrometer and electronic digital caliper with an accuracy of (0.01mm) were used to measure the product thickness variation along the depth of the cup.

Fig. (29) shows the deformation results in the same cup numerically and experimentally. **Fig. (30)** shows the comparison between numerical and experimental thickness variation along the wall of the cup and the comparison results show the error percentage between the numerical and experimental work is (5.95%) .

7- CONCLUSIONS :

1- In the wrinkle-free product, the compressive tangential stresses recover to tensile tangential stresses when the current contact area moves away from the roller. Conversely, in the wrinkling model the compressive tangential stresses induced at the roller contact zone do not fully recover to tensile tangential stresses after being deformed. This may be because the compressive stresses at the roller contact zone are beyond the buckling stability limit, resulting in some compressive tangential stresses remaining in the previous contact zone, thus leading to the wrinkling failure.

2-It can be seen that sheet thickness has an important effect in the deformation process, where the maximum plastic deformation that takes place near the round corner of the mandrel (cup bottom) results from the maximum axial force. After that, the force decreases as necking occurs at the corner of the mandrel under large axial tensile stresses. If the sheet thickness is unable to support these large axial tensile stresses, circumferential cracking and fracture at the cup bottom are expected

3-The best plate thickness to produce a cup of the aluminum plate1435 is 3mm, while the wrinkling in the cup is observed at 2mm thickness and the fracture in cup in 1mm.

4-Thickness variations obtained by the experimental work are coincide with that obtained by the numerical method.

5-From the **Fig. (30),** it can be observed that the necking occurred around the filleted mandrel edge and thickening towards the part opening.

6- The compared results showed a good agreement between them and the error percentage did not exceed 5.95% at the part opening.

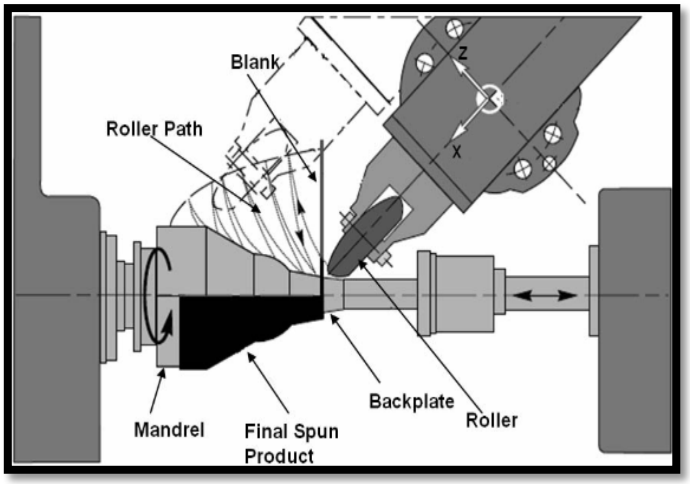

Fig. (1) Metal Spinning[Runge 1994]

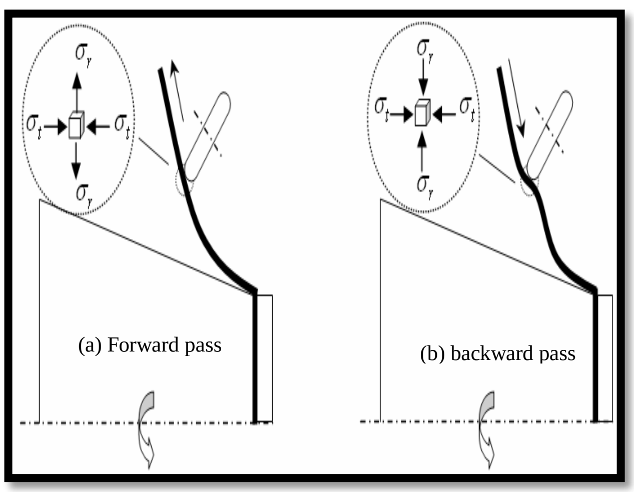

Fig. (2) Stresses Induced Through Conventional Spinning[Runge 1994]

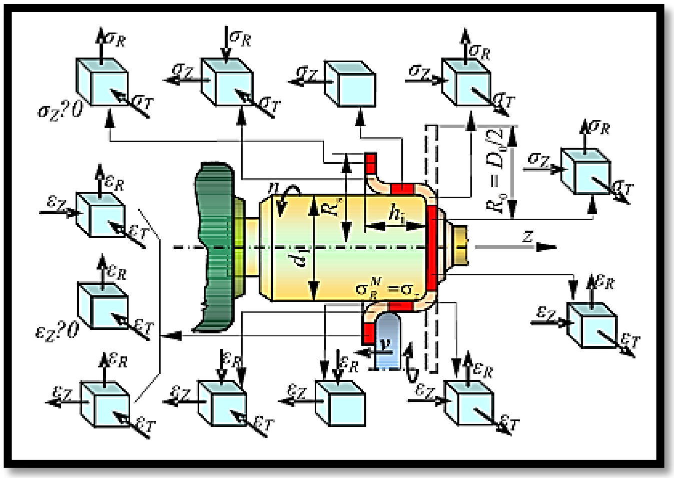

Fig. (3) Stress and Strain Distribution in Spinning Process[Lazarevic 1983]

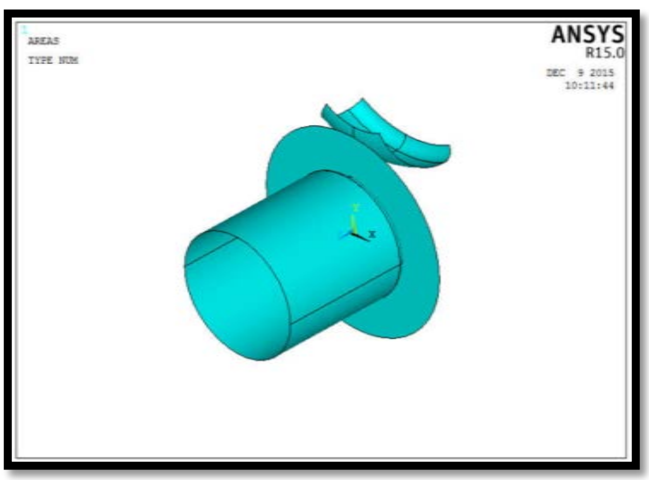

Fig.(4) Final Model in the Simulation

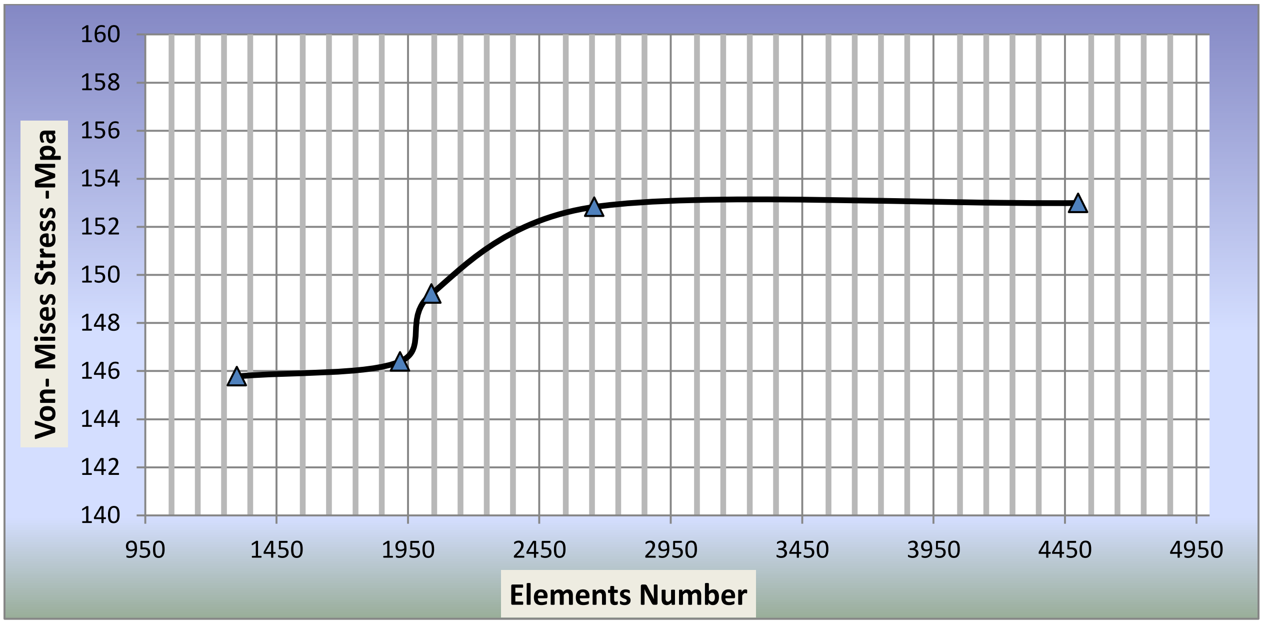

Fig. (5) Relationship Between Number of Element and Von-Misses Stress

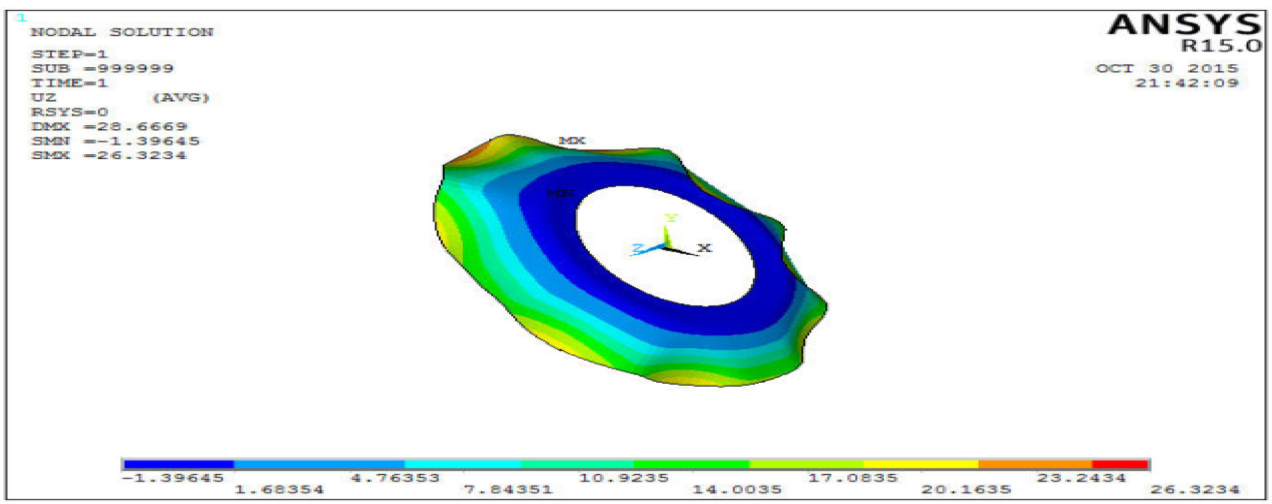

Fig.(6) Deformation in Z- Direction of 2mm Thickness

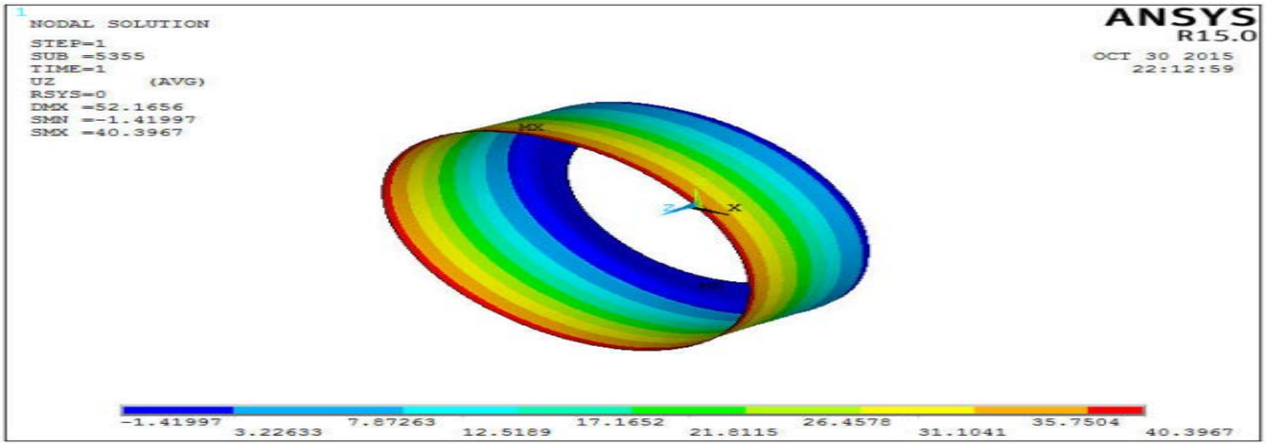

Fig. (7) Deformation in Z- Direction of 3mm Thickness

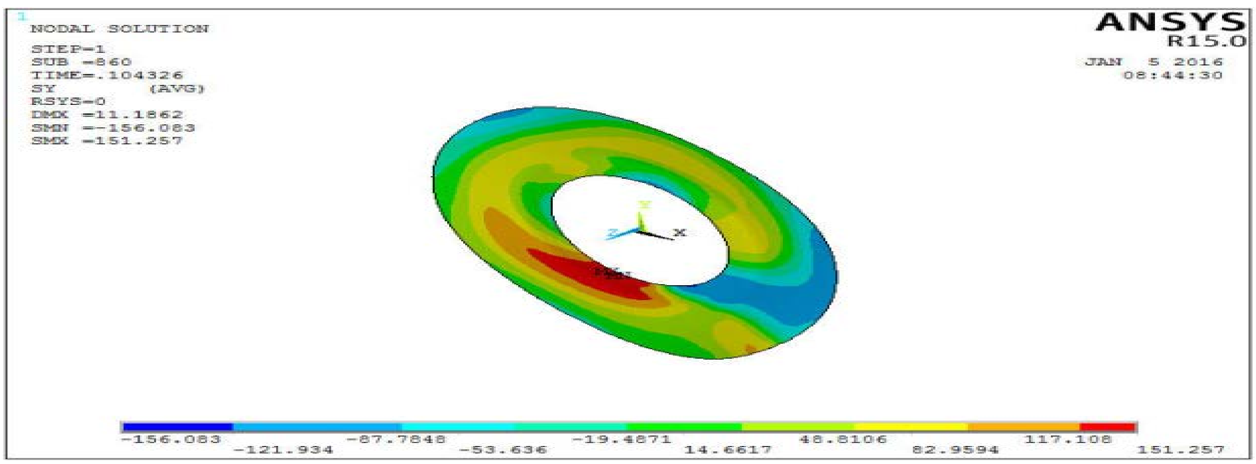

Fig. (8)Tangential Stress Distribution Along Wall of Plate (1mm Thickness)

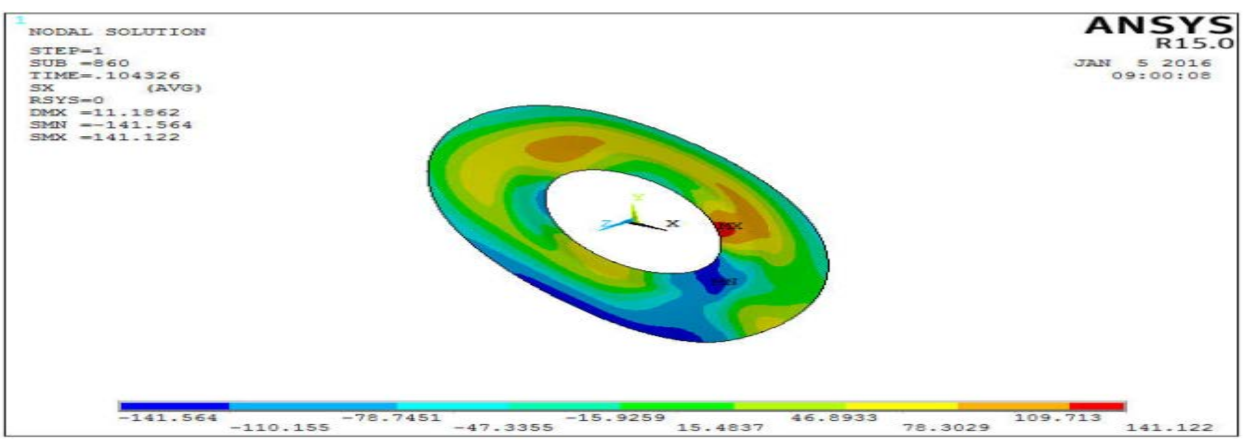

Fig. (9) Radial Stress Distribution along Wall of Plate (1mm Thickness)

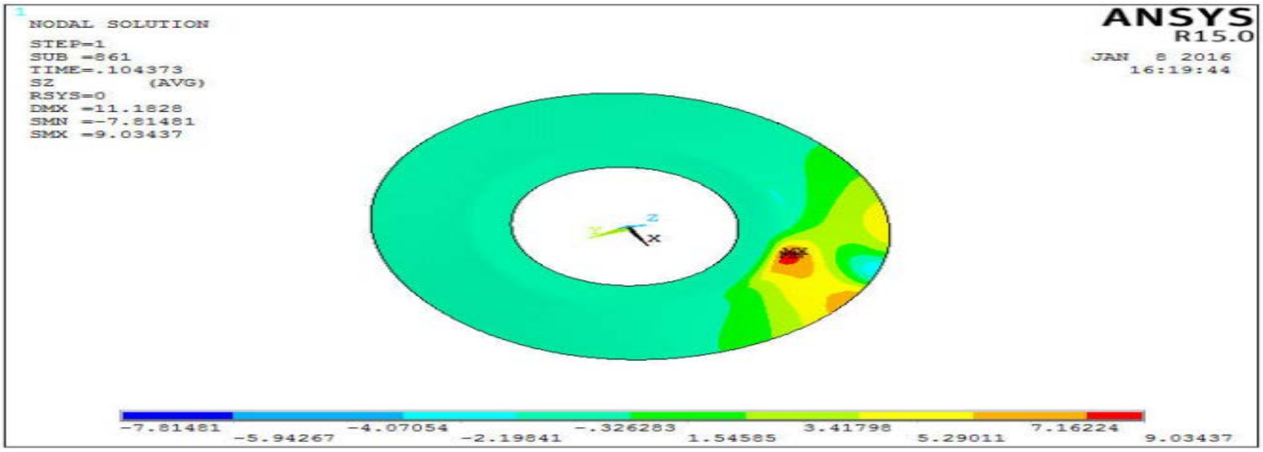

Fig. (10) Axial Stress Distribution along Wall of Plate (1mm Thickness)

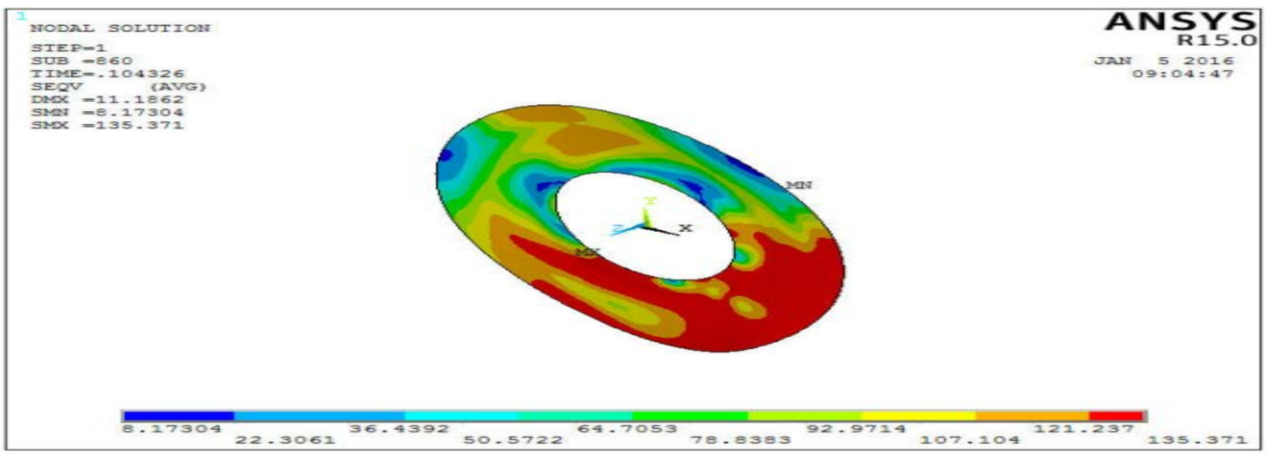

Fig. (11)Von-Mises Stress Distribution along Wall of Plate (1mm Thickness)

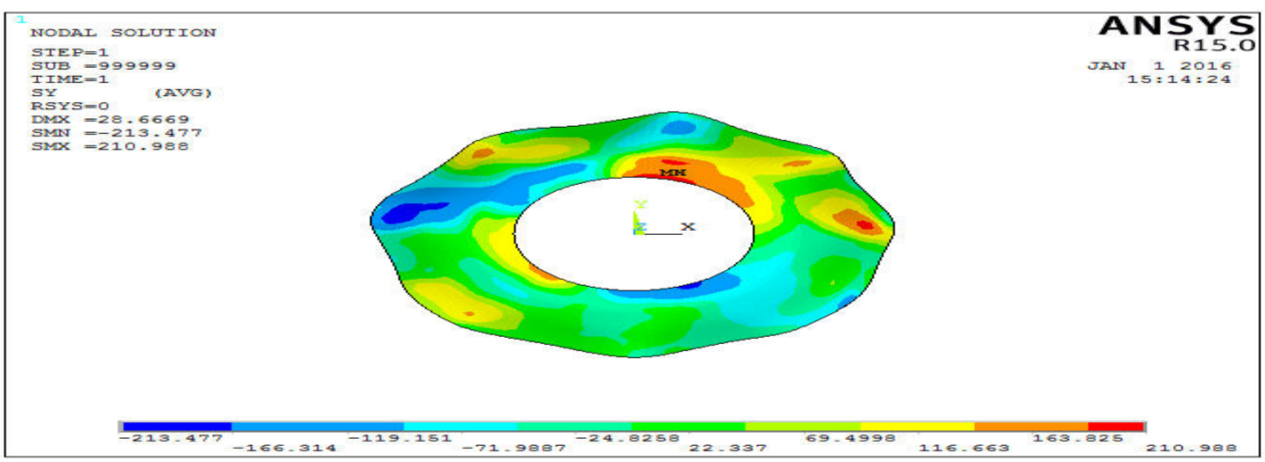

Fig. (12) Tangential Stress Distribution along Wall of Cup (2mm Thickness)

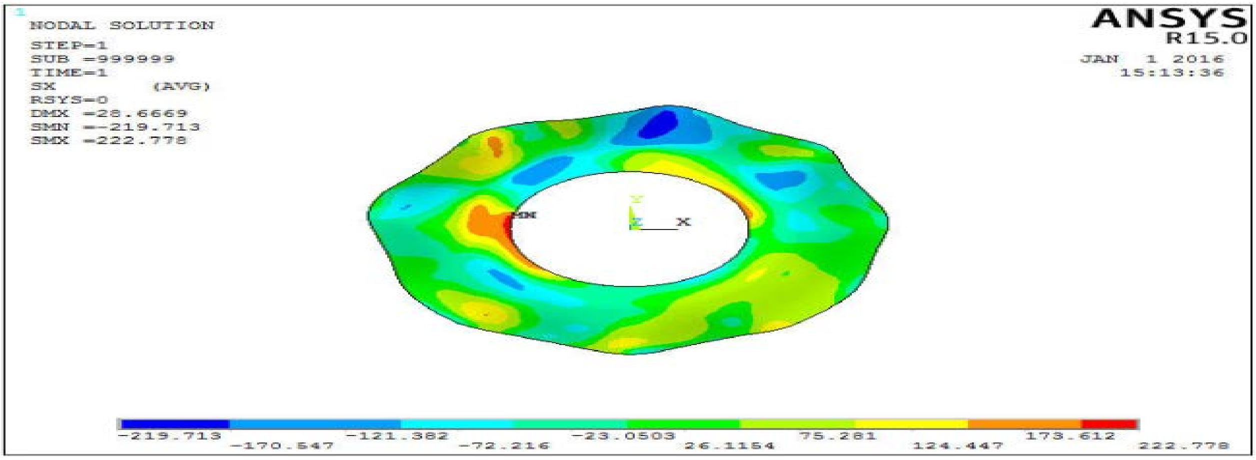

Fig. (13) Radial Stress Distribution along Wall of Cup (2mm Thickness)

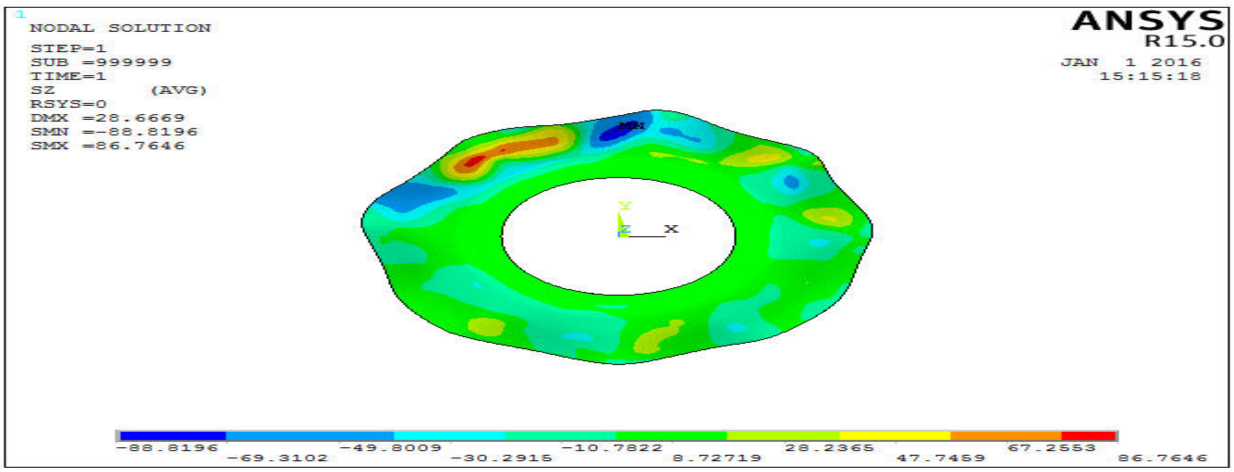

Fig. (14) Axial Stress Distribution along Wall of Cup (2mm Thickness)

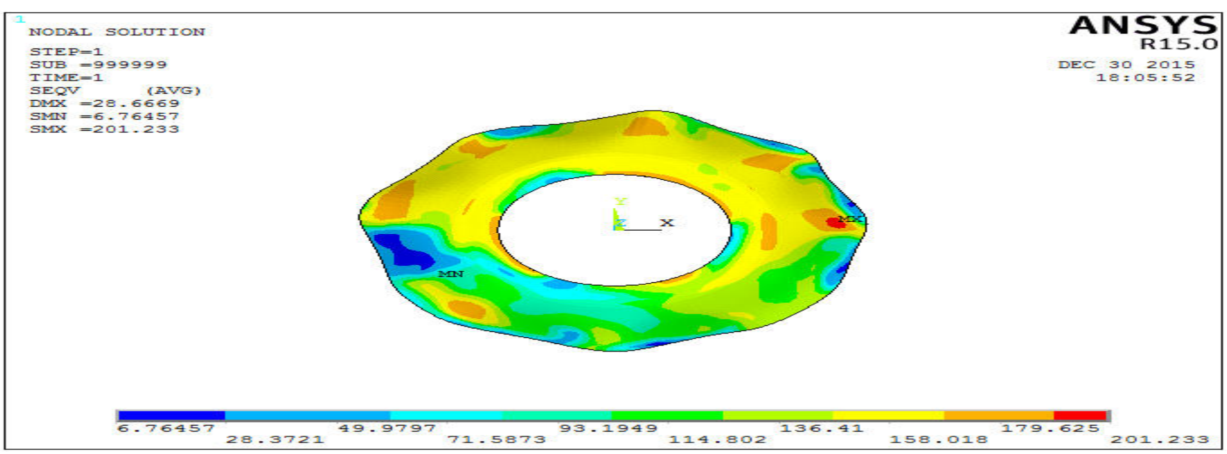

Fig. (15) Von-Mises Stress Distribution along Wall of Cup (2mm Thickness)

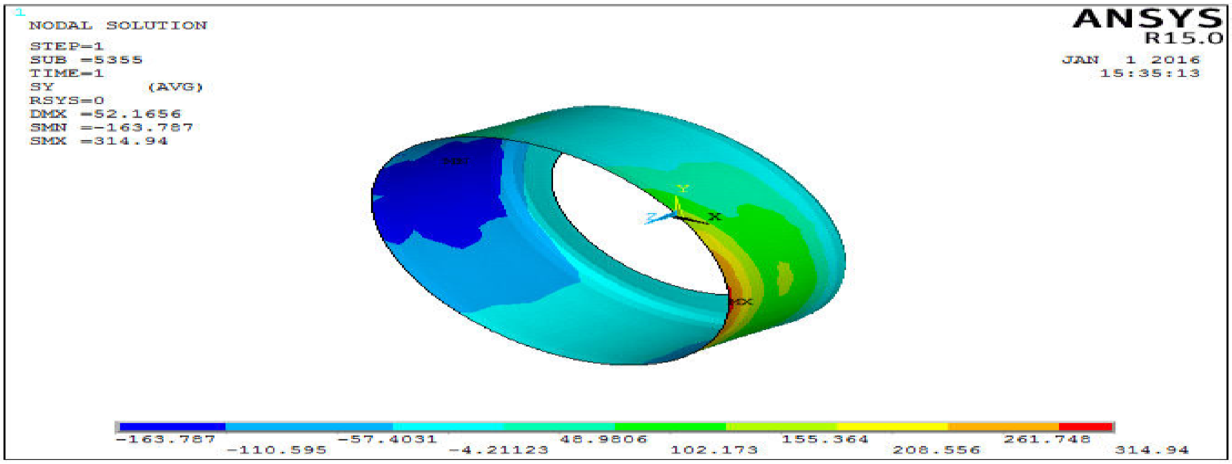

Fig. (16) Tangential Stress Distribution along Wall of Cup (3mm Thickness)

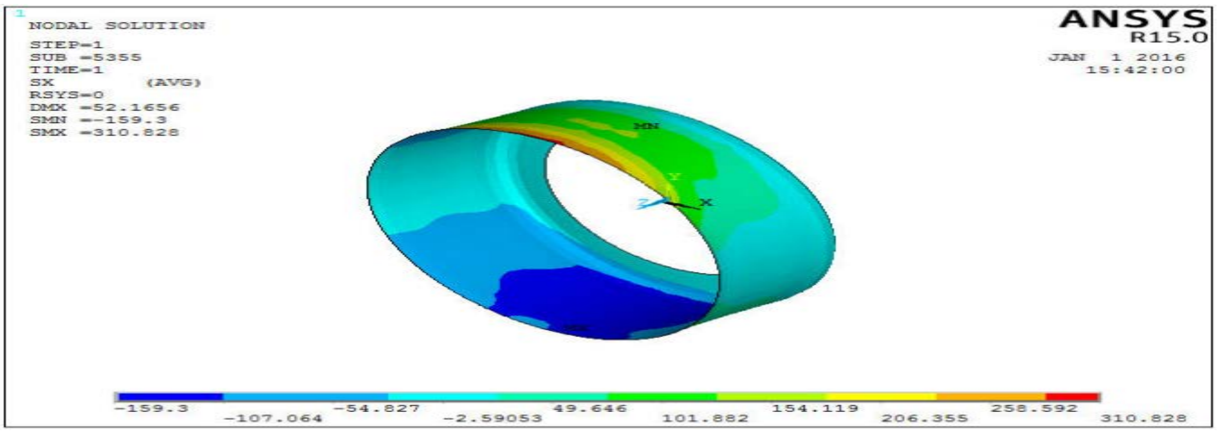

Fig. (17) Radial Stress Distribution along Wall of Cup (3mm Thickness)

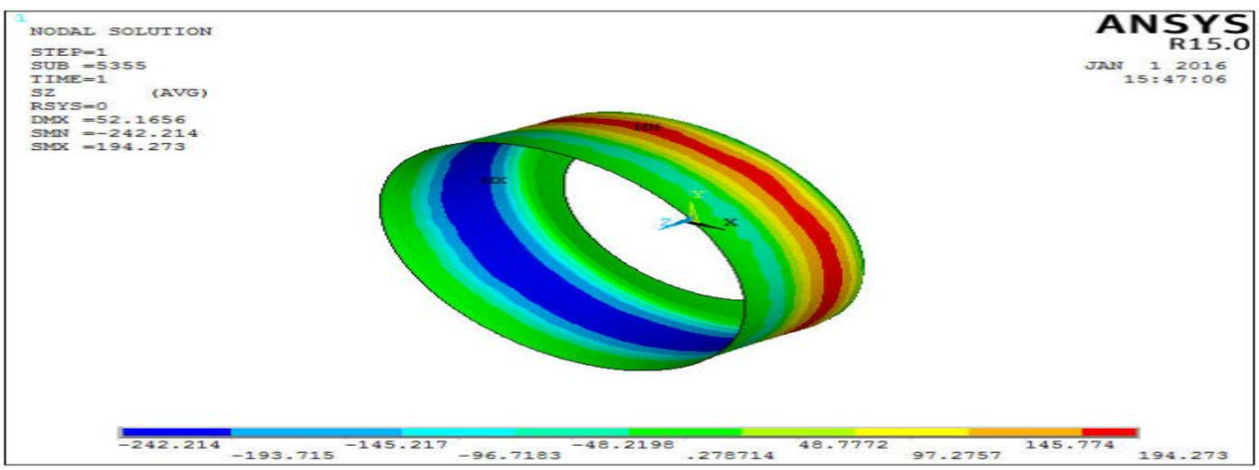

Fig. (18) Axial Stress Distribution along Wall of Cup (3mm Thickness)

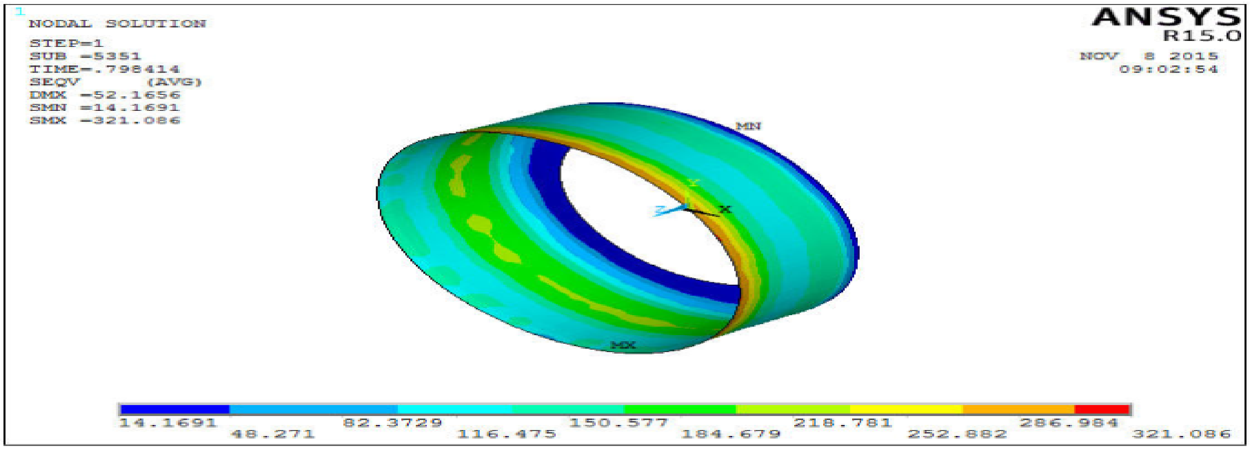

Fig. (19)Von- Mises Stress Distribution along Wall of Cup (3mm Thickness)

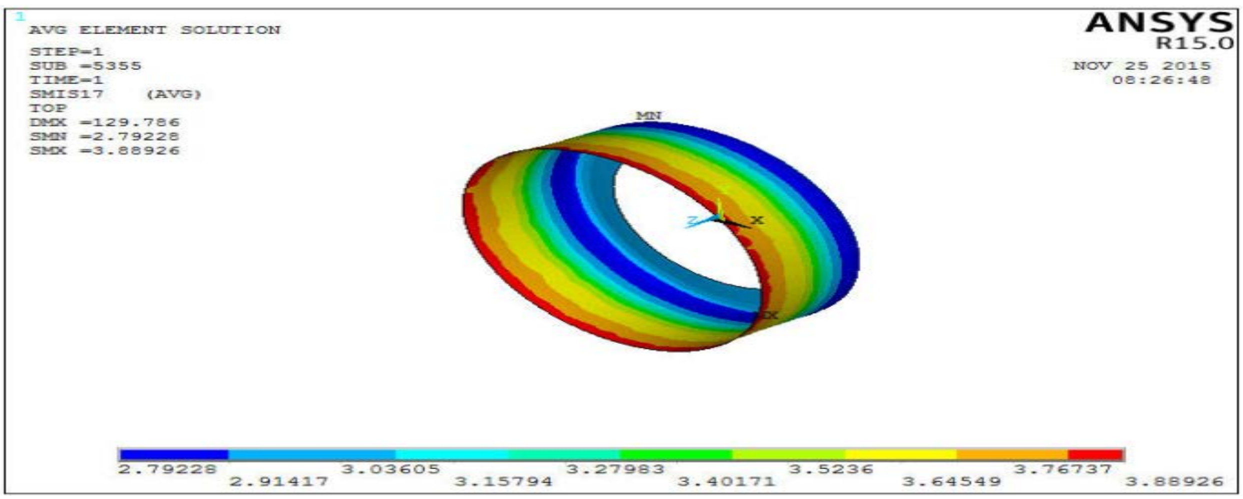

Fig. (20) Thickness Variation along the Wall of Cup (3mm Thickness)

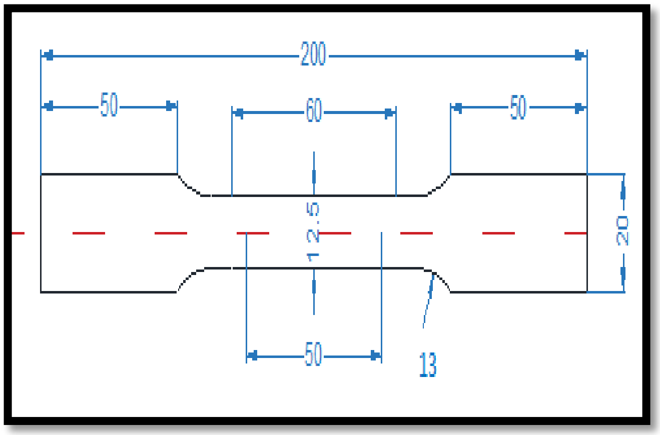

Fig. (21) The Tensile Sample Dimensions

Fig. (22) Tensile Test Machine

Fig (23) General – purpose Center Lathe

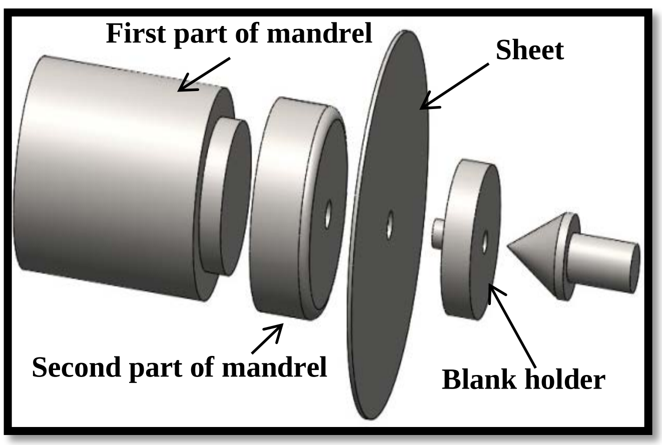

Fig.(24) Shown the Mandrel with Two Parts, Sheet and Blank Holder

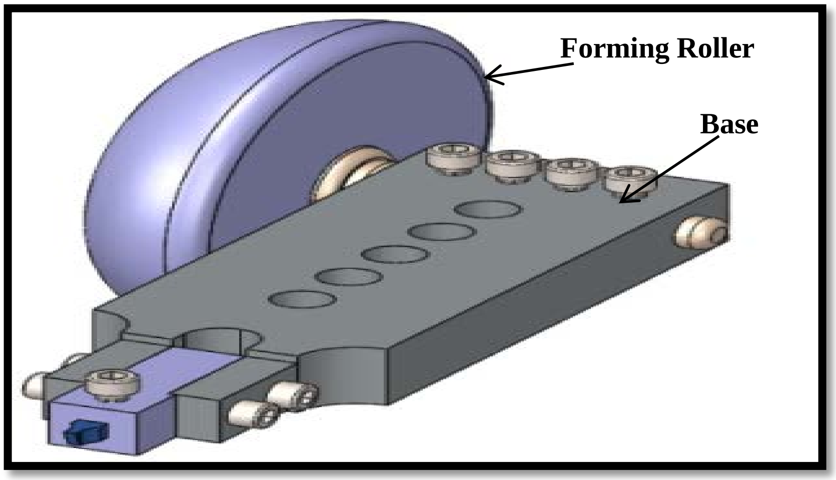

Fig.(25) Represented the Assembled the Roller with Shaft with the Base

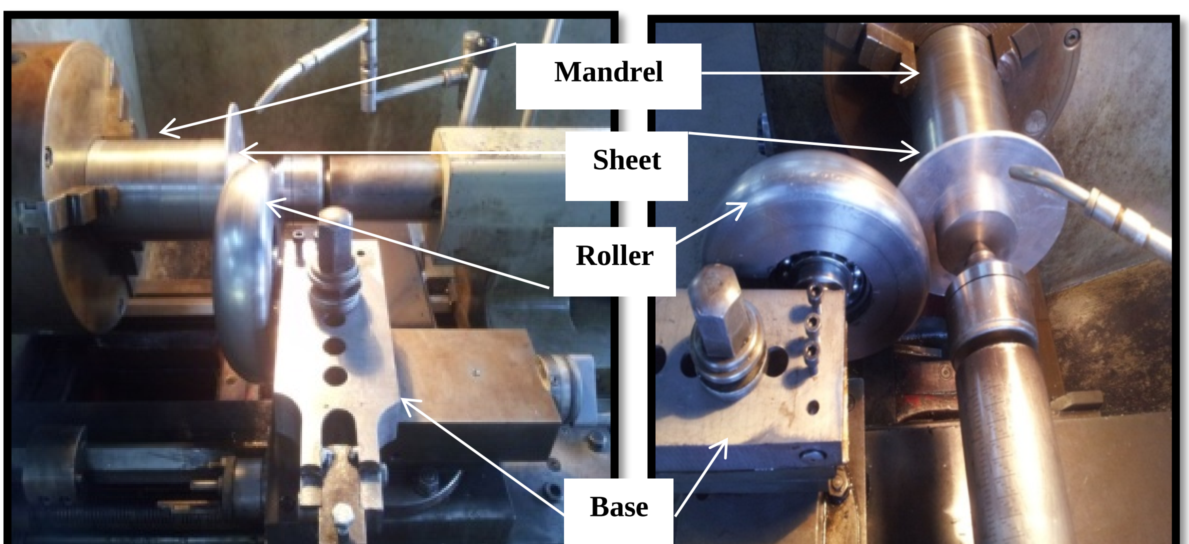

Fig. (26) Assembled Die.

Fig.(27). Shown the Wrinkling(Thickness 2mm)

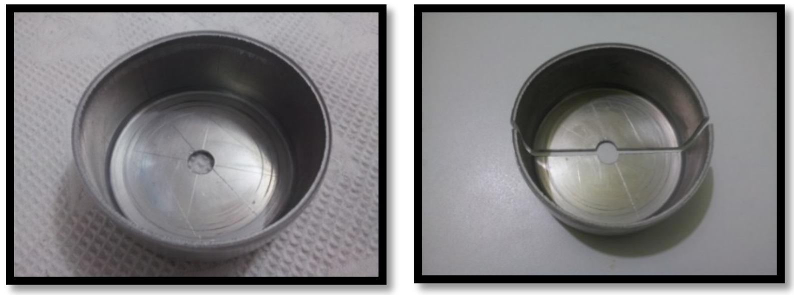

Fig.(28) Shown the Cup before and after Measuring the Thickness(Thickness 3mm)

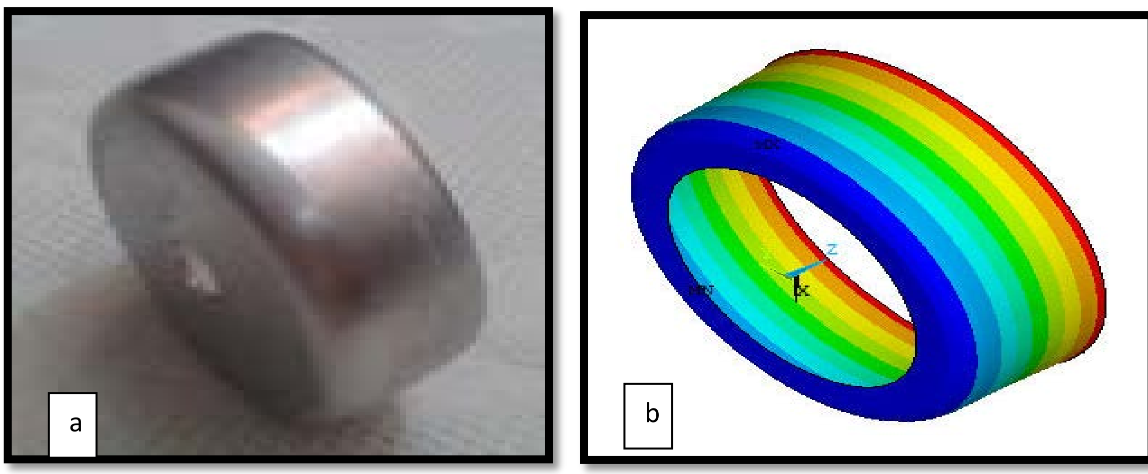

Fig. (29)Formed Cup:(a) Experimentally and (b) Numerically.

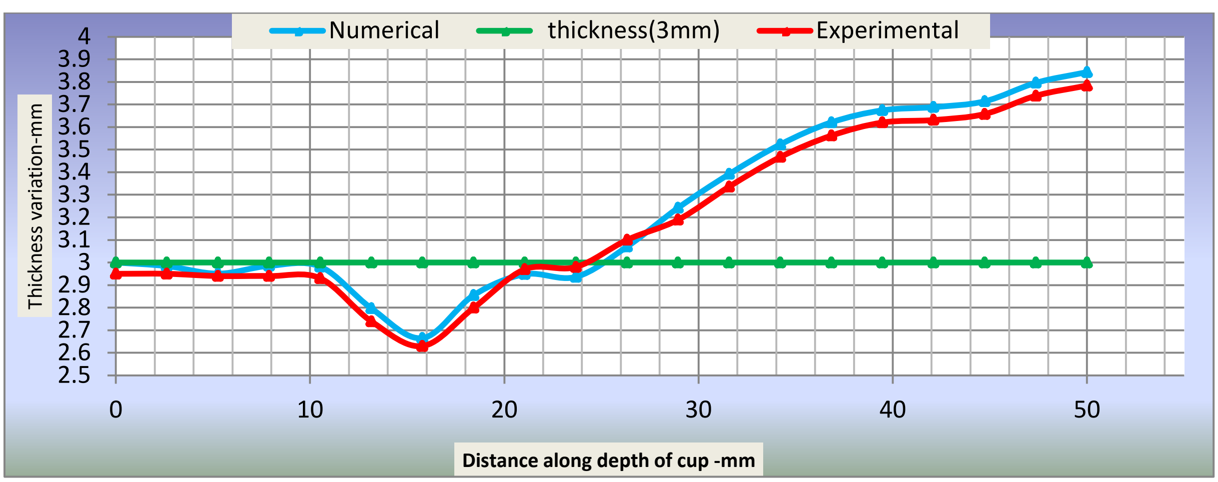

Fig. (30) Thickness Variation along X-axis

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