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EXPERIMENTAL AND NUMERICAL STUDY OF STAMP HYDROFORMING FOR PROCESSING GLASS MAT FIBER REINFORCED THERMOPLASTIC SHEETS

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Michael A. Zampaloni

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F. Pourboghrat
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By

Michael A. Zampaloni

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ABSTRACT

EXPERIMENTAL AND NUMERICAL STUDY OF STAMP HYDROFORMING FOR PROCESSING GLASS MAT REINFORCED THERMOPLASTIC SHEETS

By

Michael A. Zampaloni

The goal of this study was to verify, through experimentation and numerical modeling, that the stamp hydroforming process provided a suitable alternative to conventional methods such as thermoforming and stamp forming as a means for processing thermoplastic materials. Hydroforming involved supporting the thermoplastic sheet with a bed of viscous fluid that applied a hydrostatic pressure across the part during forming. The external support provided a through-thickness compressive stress that delayed the onset of tensile instabilities as well as reduced the formation of wrinkles due to tensile frictional forces. Preliminary experiments were conducted using a procedure that was designed and built in-house. Initial complications arose during the experimentation but the benefit of the hydrostatic pressure was qualitatively proven. The numerical analysis, conducted using MARC, showed results that correlated with the experimental trends. Overall the experimental results, coupled with the numerical modeling, showed that the hydroforming process was a viable processing method for thermoplastic materials that warrants attention based on the significant advantages in cost savings and part production accuracy.

To Suzanne and Andrew, thank you for all your love, support and patience

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LIST OF ABBREVIATIONS

$\sigma_{1,2,3}$ - Principal Cauchy Stresses

$\bar{\sigma}$ - von Mises Stress

σ'_{ij} - Deviatoric Cauchy Stress

σ_i - Stress Increment

ε_i - Strain Increment.

INTRODUCTION

There exists an abundance of fiber-reinforced composite materials that exhibit material properties such as strength and modulus that are either comparable to or better than traditional metallic materials. Typically, the composite materials have better strength to weight ratios and modulus to weight ratios than metals and can also possess excellent fatigue strength to weight ratios. Therefore, fiber-reinforced composite materials have been gaining popularity as substitutions for many of the weight critical components in the aerospace and automotive industries [1].

The fibers are the principal constituent of the fiber-reinforced material, occupying the largest volume fraction and sharing the majority of the load acting on the material. There are multitudes of commercially available reinforcing fibers ranging from glass to kevlar fibers. The choice of the type of reinforcing fiber depends greatly on the material properties desired from the finished product. The second constituent that makes up the composite material is the polymeric matrix. The matrix serves three distinct functions; it is responsible for distributing the stresses between the reinforcing fibers, it protects the surface of the fibers from abrasion, and it protects the fibers from the adverse environmental effects.

The polymeric matrix can be split into two general categories, thermosets and thermoplastics. The thermoset polymers consist of molecules that are chemically bonded by cross-links forming a three-dimensional network structure.

Thermoplastic polymers consist of individual molecules that form a linear structure with no chemical linking, these molecules are held together by weak secondary bonds such as van der Waals bonds and hydrogen bonds. Once formed, thermoset materials cannot be melted and reshaped whereas a thermoplastic polymer can be melted and reshaped as often as desired [1].

The use of a thermoplastic matrix lends itself very easily to the various high-volume and accuracy production rates that are required in the automotive industry. Some of the advantages of a thermoplastic matrix over a thermoset matrix includes: a controllable, constant molding behavior, even after being stored for long periods of time, parts can be reformed as needed, can be joined by hot-welding methods, can be bent, twisted, or otherwise hot-formed, better impact resistance and there is typically no cure time associated with these materials, thereby allowing for a much quicker forming time.

Even though these materials may present distinct advantages over the traditional metal materials, there is still the issue of manufacturing the parts while still achieving the same level of volume and accuracy. Over the years numerous manufacturing processes have been proposed to shape thermoplastic composite materials, ranging from injection molding to sheet stamping and filament winding. Shaping operations such as sheet forming, thermoforming, match die molding, contact molding, and resin transfer molding have been studied fairly extensively and are currently used by industry to manufacture polymer reinforced products of varying quality.

Due to its high success with metals, various attempts have been made to apply sheet-stamping techniques to composites. A difficulty in using thermoplastics in stamping, however, is the inflexibility of the thermoplastic material prior to heating and the heating requirements necessary to bring the matrix material to its glass transition temperature, enabling the part to be formed. The forming of straight, continuous fiber or woven fiber composite sheets typically results in wrinkling of the fibers and distortions. Randomly oriented fibers have provided good formability, but without the advantages of the highly directional properties often desired in composite parts. The more formable sheets that consist of aligned, discontinuous fibers appear to have been used with more success than continuous fibers [2].

Therefore, there exists a current need for forming and shaping methods that can produce complex structures utilizing continuous-fiber or woven-fiber composites with limited wrinkling and distortion. One manufacturing process that can achieve this desired result is hydroforming.

In hydroforming, a controllable pressurized fluid is employed against the workpiece to aid in the forming of the final part. The fluid is pressurized in an attempt to force the material to conform to shape of the punch. In addition, the fluidized pressure may also be used as a self-adjusted holding force for the material draw blank. Hydroforming differs from the conventional drawing process due to the presence of this pressurized fluid that replaces the female die typically associated with the process.

The advantages of such a process are numerous and it is receiving significant attention from the automotive and aerospace industries. Some of the advantages include highly improved drawability of the blank due to the applied pressure by the fluid, low wear rate of dies and punch, reduced thinning in the final product when compared to conventional drawing, significant economic savings associated with the decreased tooling, and the potential for reducing the amount of finishing work required [3].

In the following, a brief review of hydroforming and its potential application to forming and shaping composite structures will be presented followed by a presentation of the current state of research regarding this area of exploration. This will be followed by a discussion of the preliminary results obtained from thermo-hydroforming experiments and will then segue into the formulation method and results of the finite element analysis model created for this project.

Chapter 1

INTRODUCTION TO HYDROFORMING

The hydroforming process, as shown in Figure 1, represents a part that is being formed by a simple hemispherical punch. Prior to the start of the process the thermoplastic composite material is heated in an oven to bring the material to its forming temperature. Once the part has been heated to the appropriate temperature the workpiece is transferred to the stamping press and is placed on the clamping mechanism, as shown in Figure 1.1. Figure 1.2 shows the upper fluid chamber being lowered and the workpiece being clamped securely between the two die halves, creating a seal for the upper fluid chamber. The fluid is then injected into the chamber and is given an initial pressurization.

As the punch travels the workpiece begins to deform into a hemispherical shape initially, and finally deforms into a fully formed part after the punch penetrates deeper into the blank, Figure 1.3. While the punch is deforming the workpiece the fluid volume within the upper chamber is decreasing, thereby causing the pressure within the upper chamber to increase. This increased pressure is used as a means of forcing the material to conform to the shape of the punch.

Once the punch has reached the prescribed draw depth, the fluid can be drained and the chamber can be raised, Figure 1.4. If the part has solidified adequately the punch can be retracted and the part can be removed, if more solidification time is required, the punch can be left in place until the part has achieved solidification. If the environmental surroundings are not adequate for the part solidification then the upper fluid chamber can be drained and either cool fluid or air can be injected to help decrease the finished parts total solidification time.

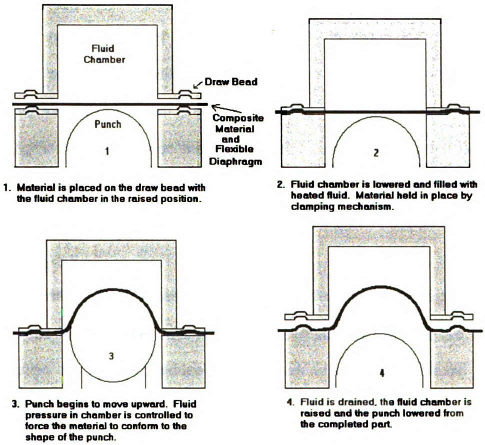

Figure 1. Schematics of a hydroforming press with a blank holding support during the forming of a cup.

The process of hydroforming, unlike conventional stamping, involves supporting the bottom of the sheet with a bed of viscous fluid during the stamping process. This external support provides a through-thickness compressive stress that will improve the formability of the sheet by delaying the tensile instability (i.e. necking). Also, this external support reduces the formation of wrinkles due to tensile frictional forces.

In the hydroforming of sheet metals, and the same issue will arise for composite materials, the difficulty lies in finding an appropriate fluid pressure-punch stroke path which will avoid rupture of the material yet control the onset of wrinkling instabilities. For the sheet metal case there have been studies conducted in an attempt to identify this optimum path. These studies, along with lessons learned, will be discussed in detail in the literature review section.

The hydroforming process, when applied to composites, must be modified slightly due to the inherent differences between polymers and metals. Heat must be applied in order to reduce the stiffness of the thermoplastic matrix by increasing its temperature between the glass transition point and the melting point. Increasing the temperature of the pressurized fluid will allow the application of heat to the composite workpiece. Since a heated fluid is used to shape the piece, good productivity can be expected from hydroforming due to the high heat transfer coefficient of the fluid.

Finally, a significant problem with stamping of composite sheets is to maintain the blank in place by using clamps. If the load needed to draw the sheet is higher than the shear yield stress of the composite, the sheet will slide from under the clamps [4]. Hydroforming requires significantly less force, if the workpiece is to be clamped at all, as the hydrostatic pressure is often sufficient to hold the workpiece in place. This last problem is often significant with composites as the polymer matrix can yield easily in the clamped region.

1.1. Hydroforming Applications

Fiber reinforced thermoplastic matrix composites are attracting the interest of the automotive, aerospace and other industries as the benefits of these materials become more readily apparent. Parts manufactured from fiber reinforced polymers are typically more expensive than their metal counterparts but their advantages, including strength to weight ratio and material shelf-life, are beginning to overweigh the short-term economic concerns.

As the cost of fuel continues to increase, the use of fiber reinforced composites in the automotive industry is starting to become very common due to the high strength to low weight ratio of these materials. Glass-mat thermoplastics (GMTs) are finding current favor in the automotive industry due to their low weight, ease of processing, recyclability, noise suppression and price . These reinforced materials can exhibit the same strength properties as sheet steel, but at a fraction of the weight [5]. Currently in production there are already several composite automobile parts such as suspension springs, space frames, body panels, and entire assemblies. There are also a multitude of others that are being planned in the near future; including the introduction of an automobile body frame created entirely from fiber reinforced composite materials [6].

The use of composite materials, especially high performance composites, has become almost synonymous with the aerospace industry. Stamp hydroforming could be used as an alternative processing method for a variety of applications such as cabin wall panels and in a variety of internal structural components.

Since the use of stamping operations is already a common occurrence throughout industry the applications for the stamp hydroforming process are too numerous to mention. The hydroforming process is currently utilized as a viable alternative to the sheet metal forming operations and the same concept can be applied to industry when trying to evaluate the potential for the use of the hydroforming process for the sheet stamping of fiber reinforced composite materials. As the increased interest in the use of composite materials increases there is also the need to determine processing methods that can create finished parts in a manner that is conducive to the economic and time constraints faced by industry. One method that may be able to provide a suitable alternative to the thermoforming and sheet stamping operations is stamp thermo-hydroforming.

Chapter 2

BACKGROUND

The idea behind this research effort started with a simple analysis of composite shaping techniques such as thermoforming and vacuum bag molding. The thought was that there are a variety of methods that can be used to shape and process fiber reinforced thermoplastic and thermoset composite materials but that each method had its distinct drawbacks such as economic cycle time concerns. The initial goal was to review these different processing methods and to identify areas that could be improved upon.

One of the processes that were evaluated was the thermoplastic sheet forming method commonly referred to as thermoforming or vacuum forming. In thermoforming, illustrated in Figure 2, the thermoplastic sheet is clamped above a negative, or female, mold and the sheet is heated. After the material is softened to its forming temperature the air beneath the sheet is evacuated through small holes that are machined into the mold. By evacuating the air from the chamber the thermoplastic material is sucked down into the mold thereby taking the required shape. Typically this process can be just a straight vacuum operation or may use a ram or plug to assist the processing (plug assisted method is illustrated in Figure 2).

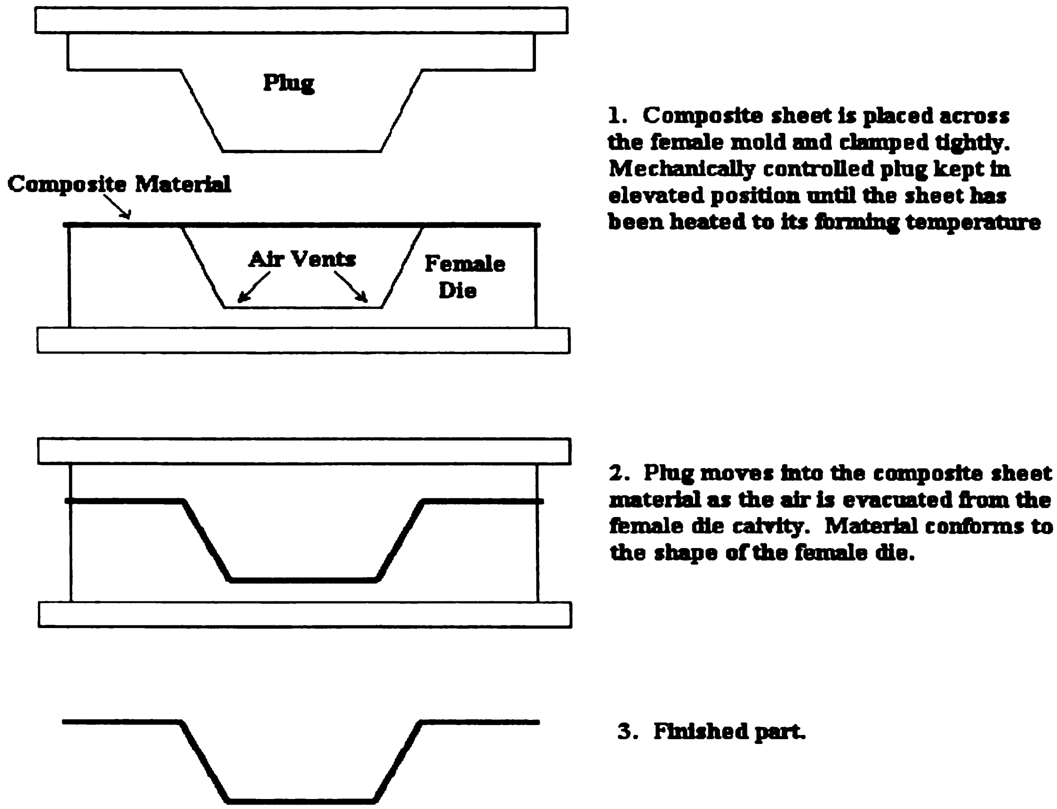

Figure 2. Illustration of the plug-assisted thermoforming processing method for thermoplastic composite materials.

While the thermoforming method is quite simple and relatively inexpensive, there are some disadvantages associated with the process. First off is that the material is very difficult to control as it moves through the lower chamber. This has the tendency to create parts that may have varying wall thickness and poor material distribution. The process has a considerable amount of waste associated with it and a fair amount of finishing is required at the completion of the process. In addition the range of shapes is limited and the ability to create parts with great detail is not attainable [7].

In general, the most important complication associated with the thermoforming process is the ability to control the onset of both rupturing and wrinkling instabilities. These instabilities typically occur due to the nature of the process. As the air is evacuated from the female die chamber the material is drawn into the chamber and conforms to the shape of the female die. One of the obstacles is the uncontrolled nature of the material movement through the chamber. The thermoforming method requires very accurate control of both the draw rate and the clamping force used to hold the material in place. In addition, the thermoforming process as shown in Figure 2 allows for the formation of parts due to pure stretch only, no material draw-in is allowed.

An evaluation of the rupturing instabilities began with an investigation into the general manner in which thermoplastic material may fracture. In the most generic sense, the first step of the fracturing process is void formation. As the material undergoes deformation the matrix and fiber material will begin to move, sometimes independent of one another. As the stress in the part increases the voids that were created during the manufacturing process will begin to grow in size. As they grow they start to come in contact with other voids, eventually, as the deformation of the part continues, enough voids will form to propagate across the part and will lead to material fracture.

The next step was to try to evaluate methods that could be used to alleviate the onset of rupturing within the framework of the thermoforming process. The attention turned to the control of fracture within the sheet metal industry. McClintock (1968) [8] and Rice and Tracey (1969) [9] conducted studies on sheet metal blanks that demonstrated rapidly decreasing fracture ductility as a hydrostatic pressure, applied across the material, was increased. Clift, Hartley, Sturgess and Rowe (1990) [10] and Hartley, Pillinger, and Sturgess (1992) [11] demonstrated that for sheet metal draw blanks, the use of a hydrostatic pressure prevented the initiation and spreading of microcracks within the metallic material.

This finding led to the idea of using a hydrostatic pressure as a means of controlling material fracture during the processing of thermoplastic materials. One method of hydrostatic pressure application that was investigated was the use of stamp hydroforming as a means for processing composite parts. In addition to the fracture control the use of the hydrostatic pressure has the benefit of aiding in the reduction of wrinkling during the forming process.

The stamp hydroforming process is used for the shaping of sheet metal parts but no information could be located about the application of the hydroforming method to the shaping and processing of thermoplastic composite materials. Therefore, it was concluded that the study of the stamp hydroforming process, as a viable alternative to the conventional processing methods such as thermoforming and stamp forming, as a means for processing thermoplastic composite materials was warranted.

Chapter 3

LITERATURE REVIEW

Through a thorough literature review there were no investigations found concerning the use of the hydroforming as a means for processing either thermoplastic or thermoset composite materials. Therefore, the main emphasis of the remaining literature review focused on the most recent experimental and numerical developments in the sheet metal hydroforming processes as well as the current state of experimental and numerical methods used for the processing of thermoplastic composites, specifically stamp forming and thermoforming.

3.1. Sheet Metal Literature Review

Based on the success found with using a hydrostatic pressure to delay the onset of fracture within metallic materials the same idea was extrapolated to the possible use of a hydrostatic force during the processing of thermoplastic materials. This led to the idea of adopting the use of sheet hydroforming currently used by sheet metal industries as a means of processing fiber reinforced thermoplastic composite sheets. In order to better understand the hydroforming process the literature review began by evaluating the current state of both the experimental and numerical sheet metal stamp hydroforming operations.

Yossifon and Tirosh (1977 – 1988) [12–16] published a series of articles dealing with the analysis of the hydroforming deep drawing process as applied to the formation of cups from metallic materials such as copper, aluminum, steel and stainless steel. The goal of the studies was to establish a hydroforming fluid pressure path, relative to the punch stroke, that would prevent part failure due to rupture or to wrinkling. Their earlier studies demonstrated the effect that excessive and insufficient fluid pressures have on the premature failure of hydroformed parts (rupture and wrinkling respectively). The purpose of the later investigations was to determine a predetermined path that can be followed to produce parts that are free from these types of defects.

In order to minimize wrinkling instabilities the fluid pressure was held to the minimum possible. The pressure relationship, based on equating the bending energy of the buckled plate and the work against lateral load (spring-type blankholder or fluid pressure) to the work done by the in-plane compressive membrane forces, included the governing parameters of friction coefficient and anisotropy. Through their work they were able to show that rupture instabilities occur when the fluid pressure being used for the hydroforming process was too high. The fluid pressure constrained the motion of the part and forced the punch through the material. The fluid pressure to prevent rupture was evaluated in terms of average friction coefficient, material properties, and geometrical considerations. Using these two fluid pressure values a range was determined that allowed for the manufacture of parts without the occurrence of wrinkling or rupturing. This theory was tested experimentally and the results were very favorable with the predicted outcomes.

Lo, Hsu and Wilson (1993) [17] expanded upon the earlier work of Yossifon and Tirosh by applying the deep drawing hydroforming theory to the analysis of the hemispherical punch hydroforming process. The purpose of this work was to determine a theoretical method of predicting failure due to wrinkling (buckling) or rupture (tensile instability) during the punch hydroforming of hemispherical cups. This work was basically an extension of the work done by Yossifon and Tirosh by incorporating a general friction-force expression into the analysis and expanding to more complicated geometries.

In order to predict failure the part was split into three regions based on the geometric characteristics of this operation. First there was a region where the part was free from contact with the die, a second region that consisted of the unsupported area termed the "lip area", and the third region that was the area of the part that had already come into contact with the surface of the punch. Along with the determination of the failure areas, the study also attempted to identify an upper and lower bound for manufacturing, a region termed the "work zone". It was proposed that if processes were run within these limits then there should be limited potential for failure. They were able to conclude that the working zone could be expanded by low friction forces, high strain hardening exponents, small drawing ratios, thick workpieces, and through the use of orthotropic materials.

Hsu and Hsieh (1996) [18] attempted to verify the theory developed by Lo, Hsu and Wilson through a series of experimental procedures. The purpose was the validation and verification of the failure prediction method for wrinkling and rupture instabilities during the punch hydroforming of sheet metal hemispherical cups. Various hydroforming pressure paths were tested during the process to validate the theory. They determined conclusively that a path that intersected the lower boundary of the working zone would lead to premature material failure due to wrinkling in every case. The same result was found for the pressure paths that intersected the upper boundary of the working zone. Through a series of varying parameter experiments the results achieved experimentally were very comparable to the theoretical predicted results.

Gelin, Delassus and Fontaine (1994) [19] experimentally and numerically studied the effects of process parameters during the aquadraw deep drawing process. The purpose of the study was to determine the main parameters that influence the aquadraw deep drawing process, specifically, the determination of the pressure in the cavity and under the blankholder as functions of process geometry, material parameters, and fluid parameters. Aquadraw deep drawing compared to hydroforming differs due to the use of a thin layer of water, subjected to fluid flow, that replaces the thin rubber diaphragm between the material and the die cavity. The investigation, limited to axisymmetric sheet metal materials, proposed a cavity pressure modeling technique based on the optimal parameters of the process instead of being modeled by the Reynolds equation.

A relationship to determine the cavity pressure was based on the material behavior, the material thickness, the die entrance radius, and the drawing ratio. The value determined was always the maximum value. The paper evaluated the influence of each of these parameters on the overall cavity pressure determination. The study referenced other experiments performed that demonstrate the effectiveness of these parameters on the determination of this cavity pressure, but no experiments were performed that physically validated the new relationships proposed through this investigation.

For the numerical analysis portion of the investigation the finite element modeling code POLYFORM was utilized to simulate the deep drawing process in order to validate these relationships. Overall, the predicted behavior was comparable to the experimental behavior for the parts analyzed.

Gelin, Ghouati and Paquier (1998) [20] and Baida, Gelin and Ghouati (1999) [21] both expanded upon the numerical work conducted in the Gelin, Delassus and Fontaine work dealing with the aquadraw deep drawing process. These two investigations expanded upon the numerical work by adding the process parameters monitoring, identification tools and general sensitivity analyses to the numerical method used as a predictor of the die cavity pressure during the deep drawing process. Overall their respective results showed very good correlation between the numerical and experimental behavior of the material.

Shang, Qin and Tay (1997) [22] spent time on the evaluation of the copper spherical shell hydroforming process by studying the effects of intermittent draw-in during the operation. The purpose of this investigation was to examine, experimentally and numerically, the effects these intermittent changes would have on the formability of the blank material. During the processing of the cups there were two main formability factors that were investigated; the radius of the die shoulder and the blank holding force. Reducing the die shoulder radius increased formability but the use of a small radius had the potential of causing premature tearing of the blank along the die shoulder. Reducing the blank holding load encouraged draw-in, inward flow of the flange material, thereby increasing the average thickness of the product and delayed the onset of material failure.

Since the radius of the die shoulder is normally fixed or limited by the product specifications then the logical approach to increasing formability would be to vary the blank holding load. During this study the copper material was formed into a nearly spherical shell using four different approaches. The first approach was a single-stage hydroforming process using two different deformation paths, one that allowed for the draw-in of the flange, and one that did not allow the draw-in to occur. The second approach evaluated the effect of a double-stage hydroforming process also using two different flow paths. The first path allowed for the draw-in during the first stage, and restricted it in the second. The second path was just the opposite, draw-in was not allowed during the first stage yet was permitted during the second stage. The results showed that during the single-stage hydroforming process, the formability of the material was greatly improved. For the double-stage hydroforming operation, the best results were achieved during the path that did not allow for the draw-in of the flange during the first stage, but did during the second stage.

3.2. Thermoplastic Forming Literature Review

Hou and Friedrich (1991) [23] investigated the development of a thermoplastic composite stamp forming process for carbon fiber reinforced polypropylene. The main goals of the research were the establishment of a useful processing technique and the control of the parameters that led to the production of a quality composite part. The useful processing conditions included process temperature, cycle time, stamping velocity and stamping pressure. The experiments were conducted using a right angle matched tool forming parts from a continuous carbon fiber reinforced polypropylene composite material. Important conclusions drawn were that the stamping pressure is related to the stacking sequence of the laminates, it decreases with an increase in the number of 90° lay-ups due to transverse flow. The stamping temperature was determined to be at a range that is slightly higher than the melting temperature of polypropylene and that the stamping pressure had more influence on the final part properties than the stamping velocities.

Hou (1997) [24] continued the earlier work of Hou and Friedrich by applying the same concepts and principles to the stamp forming of continuous unidirectional glass fiber reinforced polypropylene composite materials. The goal was the same as before, to establish a useful processing technique that leads to the production of a quality part. Experimentally the hold-down pressure became the limiting factor for the stamp forming process.

Harper (1992) [25] investigated the most recent developments of the thermoforming processing methods for shaping thermoplastic matrix composites. Some of the major disadvantages associated with the thermoforming method were discussed and addressed. The disadvantages included: the difficulty of stretching the material when trying to clamp it to the frame, the possibility for the material to be incompressible in thickness due to the density of the packed continuous fibers, buckling concerns, the speed of the forming requirements and the difficulties associated with the control of the fiber placement.

Pegoretti, Marchi and Ricco (1997) [26] evaluated the anisotropic fracture behavior of polypropylene cups created by a vacuum thermoforming process. The anisotropic behavior was studied through an elasto-plastic fracture mechanics approach. Experiments were conducted using samples with high length/width ratios drawn to depths of 100 and 58 mm. Results illustrated that the anisotropic behavior of the polypropylene was pronounced as the thermoforming draw-ratio increased. In all cases, the yield strength was found to be higher along the drawing direction

O' Bradaigh, McGuinness and Pipes (1993) [27] studied a general-purpose finite element simulation code that predicted the stresses and deformations in a composite sheet subject to, predominantly, planar forming forces during a diaphragm forming operation. The numerical analysis method incorporated the kinematics and rate dependence of the instabilities encountered during manufacturing, while still allowing for geometric generality. The two most limiting modeling assumptions made through this study were the planar restrictions and the purely viscous response assumptions. The finite element modeling was accomplished utilizing FEFORM, based on the finite element analysis (FEA) code PCFEAP.

In conjunction with the FEA analysis, experimentation was performed using a heated circular punch and mold. The objective was to investigate the stress and deformation states of the composite sheet and to draw conclusions regarding the sensitivity of the shear-buckling phenomenon to the different process parameters that could be varied including the uniform radial velocity, the uniform radial pressure, and pressure loading. The results showed very good agreement between the FEA modeling and the experimental results in the fiber direction. Somewhat poorer results were found in the transverse direction.

McGuinness and O'Bradaigh (1995) [28], through experimental and numerical work, focused on the occurrence of buckling during sheet forming of fiber reinforced composite materials into a hemispherical mold. The purpose of this experimental procedure was to study the effect that changes to the preform shape would have on the buckling patterns observed during the forming of quasi-isotropic laminates. More specifically, the goal was to determine if a square laminate was less prone to buckling at the 45° point than at the 0 and 90° points.

The physical portion of the experiment was accomplished using a computer-controlled thermoforming autoclave; the parts were not mechanically stamped but were formed by utilizing a pressure differential. Four types of preform shapes were evaluated; square, large rectangular, small rectangular and a truncated square preform achieved by cutting two corners off the square preform. No definitive conclusions were drawn from the experimental study about which shape outperformed the other. The numerical analysis results showed very good correlation with the experimental results. Overall conclusions of the study illustrated that for unidirectional and cross-ply laminates the shear stress at 45 ° to the fiber directions controlled the buckling pattern. For the quasi-isotropic laminates, the axial compressive stress of the fibers that ran tangent to the buckling site determined the occurrence of the instability.

Long, Rudd and Middleton (1996) [29] were concerned with the development of mathematical modeling techniques that describe the deformation of continuous random fiber reinforced thermoplastic materials during preform manufacture. The investigation used a numerical finite differencing scheme developed to simulate the material's behavior. The local stresses and strains were derived from equilibrium of forces, mass continuity, and plasticity theory. The model was verified through an experimental axisymmetric stretch forming process using both a hemispherical and a wheel hub punch. The main goal of the study was to develop a modeling method that could be extended from the simple hemispherical and wheel hub punch geometries to more complex forming operations.

Overall, the results from the modeling process were relatively similar to the actual experimental results. The conclusions of the paper were that the results could be used for the material tested, but that the assumptions that went into the calculations should be re-evaluated before changing the material. This is due to the changing nature of different composites as they are manufactured.

Koziey, Pocher, Tian and Vlachopoulos (1997) [30] presented the advantages and disadvantages of various constitutive equations for the description of the extensional behavior of polymers. The study's purpose was to introduce and evaluate the following mathematical models for the prediction of wall thickness distributions for thermoformed parts: Mooney-Rivlin model, Ogden model, G'Shell model, Modified G'Shell model and K-BKZ model. The conclusions drawn were that the best results were achieved through the Modified G'Shell model but that these results were still less than perfect. The reason for this discrepancy was attributed to the fact that uniaxial data was used in an attempt to predict biaxial deformations.

Hsiao and Kikuchi (1997) [4] developed a methodology of analyzing the deep drawing process for thermoplastic composite laminates where the processing governing equations and the corresponding material properties of the composites were derived by the homogenization method. The finite element modeling at the macroscopic and microscopic levels was then developed for the simulation of the deep drawing process. In this study, numerical results from this methodology were demonstrated and compared with experimental observations.

The study proposed to break the process into two distinct stages; Thermoforming and Cooling. The governing equations for each stage were developed and the homogenization method was utilized to make these equations adaptable to the FEA environment. The homogenization method was able to de-couple the governing equations into a set of microscopic and macroscopic equations. The microscopic equations accounted for the characteristic deformation within the microstructures while the macroscopic equations accounted for the average deformation for the composite structure. The microscopic equations were solved and used as input information for solving the macroscopic equations within the FEA analysis.

The process was verified by running experiments utilizing cylindrical and square punches. The experimental results for the fiber orientation prediction compared very favorably with the predicted theoretical results for both punches. Overall the numerical analysis proposed showed good results for predicting the macroscopic and microscopic stresses and strains, the fiber orientation and the final shape.

Chapter 4

EXPERIMENTAL WORK

In this section, the experimental apparatus designed and built in-house for sheet composite hydroforming will be described, followed by the results from the preliminary experiments that have been performed using a hemispherical punch.

4.1. Experimental Apparatus

The experimental apparatus was built around a double action servo press, Figure 3, manufactured by Interlaken Technology Corporation, Eden Prairie, Minnesota. The double action of the press refers to the fact that the clamping mechanism can move independent of the punch mechanism. This allows for the boundaries of the composite draw blank to be clamped while the punch pushes the composite sheet into the die cavity filled with supporting fluid. The ability to independently control both the clamp and the punch affords the opportunity for various modifications of the experimental procedure.

The first step in the creation of the experimental set-up was to design a special die set that could be used to accurately study the hydroforming process. The initial design started with a simple limiting dome height (LDH) test die that is currently used for the evaluation of lubricants in the sheet metal industry. The LDH die is essentially a pair of cylinders that are clamped together after placing a draw blank between them. The punch moves through one chamber, meets the material and stretches it into the second cylinder. The clamping mechanism typically contains a draw bead thereby allowing for the study of pure stretch only. Figure 4 schematically represents the press with a simple LDH die set in place while Figure 5 is a schematic drawing of the simple LDH die set that was used prior to modifications for the hydroforming process.

Figure 3. Double action servo press 75 manufactured by Interlaken Technology Corporation, Eden Prairie, MN.

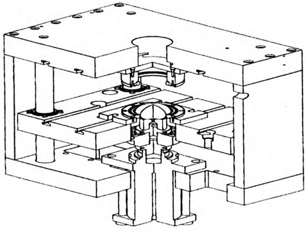

Figure 4. Schematic of the double action servo press with a simple limiting dome height test die in place.

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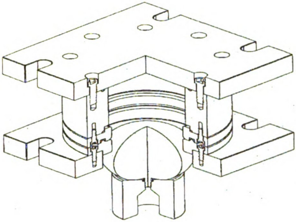

Figure 5. Schematic of a simple limiting dome height (LDH) test die set.

The overall experimental process as illustrated in Figure 6 started with a few modifications that were made to the LDH die set. Initially the die was retrofitted with four ports; one for measuring the pressure within the fluid cavity, one for injecting fluid into the die cavity, one for removing the air from the chamber during the fill process and one that is used to measure the fluid temperature within the chamber during the process. Figure 7 is schematic illustrating these changes while Figure 8 is a picture of the in-house designed die that was used for studying the hydroforming process as it was applied to composite materials.

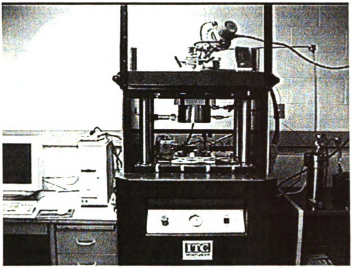

Figure 6. The modified Interlaken servo press 75 used for the hydroforming of composite sheets.

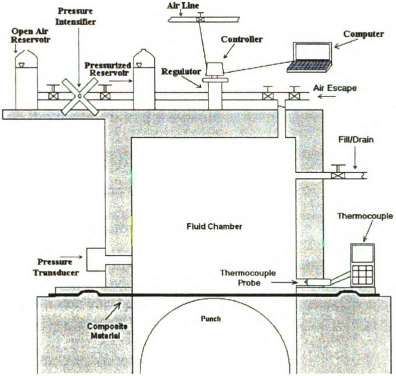

Figure 7. Schematic View of the Experimental Apparatus used for Hydroforming Hemispherical Cups [31].

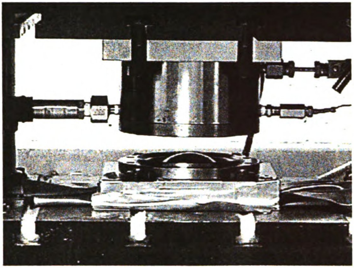

Figure 8. The in-house designed die set for hydroforming composite sheets.

Attached to the fluid line is a regulator/controller that is used to accurately control the fluid pressure within the die cavity as the composite material is stamped, Figure 9. If the pressure is too high, based on a user-defined algorithm, then the pressure in the system is reduced to the appropriate level. If the pressure is too low then the regulator pulls additional pressurized fluid from a pressure vessel that is in line with the rest of the system. A pressure intensifier is used to supply the necessary volume and pressure to the reservoir prior to the start of the hydroforming process, Figure 10. The details of the user-defined pressure algorithm are still being developed through a series of multiple testing cycles.

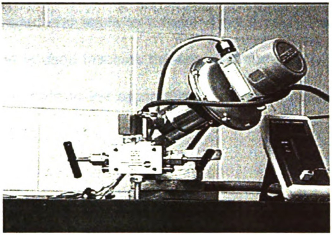

Figure 9. Regulator and Controller used for the control of the fluid pressure within the forming chamber.

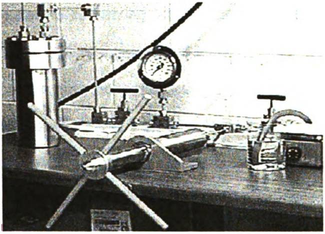

Figure 10. Pressure intensifier and pressure reservoir used in the hydroforming experimental set-up.

In addition to the pressure controlling modifications, the system is also designed to take advantage of the heating that is required to form thermoplastic materials. Prior to entering the fluid chamber, the fluid is heated to a temperature of approximately 300 degrees Fahrenheit using a hot plate. Through the injection of heated fluid, the natural cooling that typically occurs during this operation is eliminated and leads to a better-formed part. The second type of heating source that is used involves the use of a convection oven to bring the thermoplastic test sample to the appropriate forming temperature, which in this case is around 200 °F.

The third and final heating source used for this manufacturing process involves the heating of the die and tool prior to placing the sample in the experimental apparatus and during the course of the process. Heating tape is placed around the upper fluid chamber and the lower punch chamber. While the material is being heated to its forming temperature the heating tape is used to preheat the die surfaces. This ensures that the part is not prematurely cooled prior to the closing of the draw bead and the injection of the heated fluid. Once the draw blank is in place and the draw bead is clamped in place, the heating tape is used to ensure that the process maintains a temperature of around 300 °F during the entire process cycle.

4.2. Hydroforming Challenges

The challenges that are present during the stamp hydroforming of composite materials process can be classified into three broad categories: material, fluid pressure and temperature. The material challenges refer to the choice and behavior of the draw blank material. One of the major obstacles concerns the delicate balance between the fluid pressure and the ductility of the material chosen for the hydroforming process. The fluid pressure needs to be high enough to bend the work piece through its radius of curvature to conform to the shape of the punch yet the material needs to be ductile enough to take this bend without rupturing.

The second material challenge concerns the macroscopic and microscopic behavior of the material. The behavior of the thermoplastic materials during the processing operation is not easily predicted using just the macroscopic properties of the material. When dealing with the composite structures, the better predictor of overall material behavior comes from a very thorough understanding of the microstructural behavior of the material. It is important to understand how each fiber moves in relation to the other fibers and how their movement affects the overall matrix in order to predict the overall shape of the finished part. It is also important to recognize that these microscopic changes in material behavior are not only going to be dependent on the punch displacement but also on the temperature, fluid pressure and strain rate alterations.

Currently the initial experiments were based on the assumption of macroscopically isotropic material behavior and led to the determination of a stress and strain failure criteria based on this assumption. While this macroscopic isotropic behavior is known to be a weak assumption it does provide an adequate starting point for the determination of the failure criteria, criteria that will be altered as more experimental results become available. Since there currently is no quantitative experimental data to compare against, the discussion concerning the stress and strain failure criteria will be left to the section on numerical analysis results.

The second classification of hydroforming challenges to be discussed is the fluid pressure category. Fluid pressures within the upper fluid chamber that are too high will cause the material to move through the radius of curvature much faster than the ductility of the material will allow. This will lead to premature rupturing of the draw blank material. On the other hand, if the fluid pressure is too low then there is not enough stretching being forced to occur during the process and the material will be prone to wrinkling.

Therefore there is the need to establish an upper and lower limit on the fluid pressure, as it relates to the punch stroke, to determine an optimum fluid pressure punch stroke path to ensure limited rupturing and wrinkling failures of the finished part. A generalized curve is illustrated in Figure 11 to help demonstrate one of the goals of the experimental research, the determination of the optimum fluid pressure-punch stroke path for the stamp hydroforming of glass mat fiber reinforced polypropylene thermoplastic material.

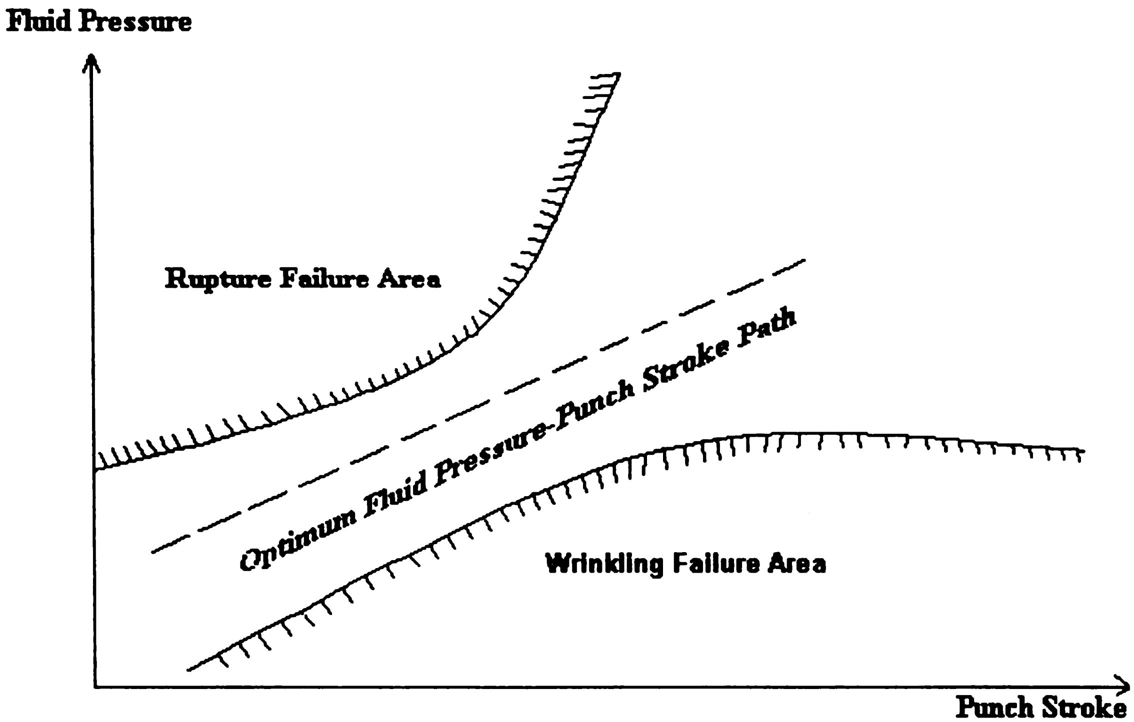

Figure 11. Generic curve illustrating the optimum fluid pressure-punch stroke path for the stamp hydroforming process.

The third classification of the hydroforming challenges is the temperature category. Thermoplastic material at room temperature is very brittle and will shatter if put through the stamping process. In order to shape thermoplastic materials they must first be heated to, or above, their glass transition temperature or forming temperature. The forming temperature of the material refers to the temperature at which the matrix has become malleable and can easily be shaped. This is currently done by placing the polypropylene thermoplastic sheets in a simple oven and heating them for sixty minutes at 300 °F.

While the sheets are being heated the fluid that is going to be injected into the chamber is also heated to 300 °F using a hot plate. Simultaneously, heat tape is placed around the upper fluid chamber and the lower punch chamber in order to preheat the metallic surfaces prior to the start of the hydroforming process. Once the material has reached its forming temperature it is placed across the draw bead and the system is clamped. The fluid is injected into the chamber and the process begins. In order to try to keep the process as isothermal as possible the heating tape continues to heat the entire chamber through coordination with a thermocouple placed within the upper fluid cavity.

The challenge is the timing involved with all these systems. As mentioned earlier the material is heated for approximately sixty minutes. During that time the die surfaces and the fluid are also heated to their respective temperatures. The thermoplastic material does not retain heat for long periods of time and can typically lose between 25 – 50 °F during the transfer between the oven and the die. Therefore it is important to keep the transfer time to a minimum while ensuring that the die and fluid will not remove heat from the material before it has been shaped by the punch.

4.3. Current Experiment, Hydroforming with Hemispherical Punch

Currently the experimental set-up is designed to fabricate simple four-inch diameter hemispherical cups using glass mat fiber reinforced polypropylene thermoplastic material that is supplied through a partnership with Azdel Inc. The choice of this punch geometry was based on its popularity in current metal and composite research [17, 18]. By performing experiments using the hemispherical punch, the data collected can be readily compared against the data that exists for operations such as composite sheet stamping, thermoforming, and even sheet metal hydroforming operations. Figure 12 illustrates a sheet of the Azdel glass mat fiber reinforced polypropylene thermoplastic material prior to and at the completion of the stamping process.

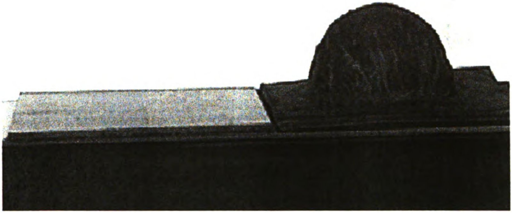

Figure 12. Sheet of the Azdel glass mat fiber reinforced polypropylene thermoplastic material prior to and at the completion of the stamping process.

One of the unique opportunities associated with the choice of the hemispherical punch is that it allows for the study of material tearing without wrinkling during the hydroforming process. This allows for the optimization of the fluid pressure and heating schemes that can be maximized to allow for deeper drawing of the parts before rupturing.

Through a series of preliminary experiments the initial result for the test material was not exhibiting the trends that were anticipated. The parts that were hydroformed were found to fail at lower draw depths than the parts that were formed using no resisting fluid. After a careful analysis of the experimental procedures it was discovered that the results were not turning out as expected due to the complications associated with the process being built in an attempt to counteract the effects of gravity. As the fluid was injected into the chamber it was initially pressurized. This initial pressurization, coupled with the gravitational effects of the heavier material caused the material to sag at the unsupported regions, material regions not in direct contact with the punch, illustrated in Figure 13.

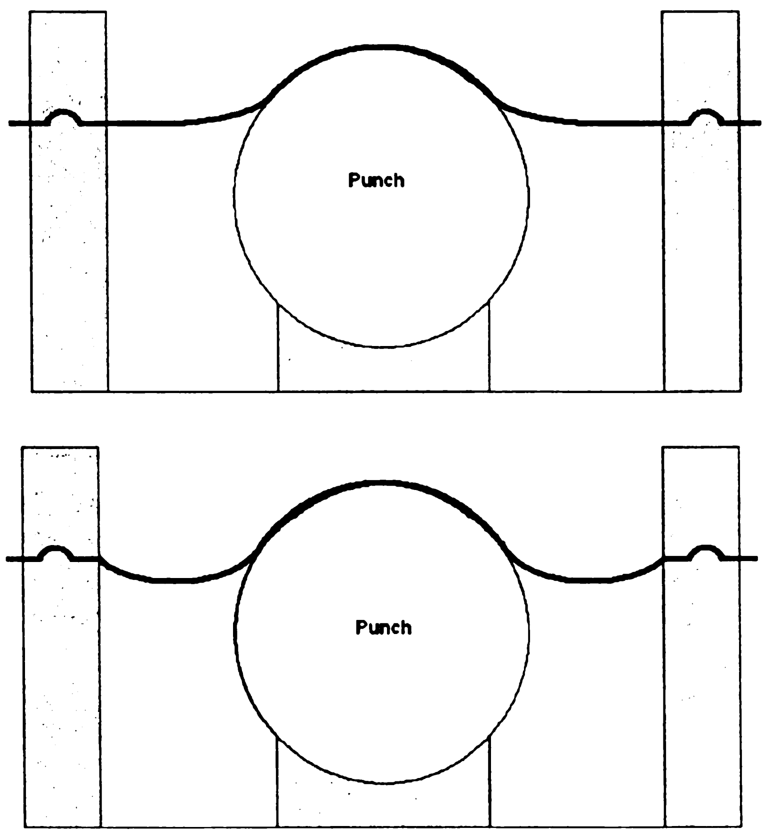

Figure 13. Example of material sag in unsupported regions of the initial hydroforming die design.

This fluid-induced sag caused the material to experience an additional tension equivalent to the fluid pressure times the area of the unsupported region. This additional tension within the material led to premature rupturing of the part as the fluid pressure increased within the chamber. In addition to the increased tension within the part, the material was also subjected to a reverse bending effect. As the punch came into contact with the sagging material it reversed the direction of the material flow and added an additional stress to the part.

In an attempt to still validate the method and to explore different design ideas, the process was conducted using a vinyl diaphragm material in place of the counteracting fluid. The vinyl material was a stiffer material that was used to simulate the addition of a hydrostatic fluid pressure only at the material locations that were in direct contact with the punch. As the punch moved into the draw blank material the vinyl diaphragm counteracted the motion and added a pressure at the location of the material that was in contact with the punch. Due to the stiffness of the vinyl material the unsupported regions of the draw blank material were unaffected by the use of this diaphragm, therefore the only sag that could occur in the material was due to the natural gravitational effects.

Figure 14 compares the parts that were formed without a counteracting hydrostatic pressure and a part that was formed utilizing the diaphragm-induced hydrostatic pressure. The use of the hydrostatic pressure demonstrated appreciable qualitative increases in draw depth for the hemispherical part.

Based on the nature of the diaphragm material, and the experiments being conducted, the results of the concept were not quantified but rather were used just as a proof of the general concept. Variations to the die and to the experimental procedure will be adopted in an attempt to accurately quantify these results, but the preliminary results do illustrate the potential benefits of this method. The further experimentation and method validation will be discussed in the Future Work section.

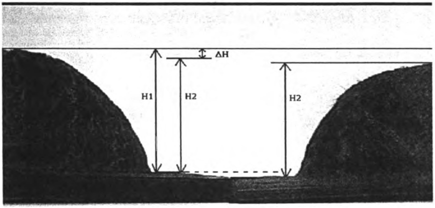

Figure 14. Comparison of the hemispherical part formed with an applied hydrostatic force and with no applied pressure, respectively.

The current experimental set-up requires the use of the draw bead to fix the borders of the material during the forming process. This forces the part to be formed through stretching of the workpiece only. One of the changes that is presently being adapted into the system is to allow for the material to be drawn in as it forms. The fluid pressure within the chamber will force the excess material to form to the surface of the punch, allowing the parts to achieve a deeper draw while still maintaining a uniform part thickness. This may lead to more wrinkling instabilities but it will allow for the optimization of the process with regard to both wrinkling and rupturing instabilities. These issues will be addressed in future experiments in order to try to hone this process in an attempt to correlate the theory with the experimental results.

Chapter 5

NUMERICAL ANALYSIS

One of the most important steps in the development of a new product is determining a numerical method for the prediction of final part geometry and for the optimization of the process to meet certain product specifications. When working with composite materials this becomes even more critical since these types of materials are prone to wrinkling and buckling during the manufacturing process. In addition, when altering composite materials, anisotropy may be introduced in the part by the rearranging of the fibers within the matrix.

One very important tool that can be used to aid in the optimization process is finite element analysis (FEA). FEA can be used as a predictor of part geometry as changes are made to the fluid pressure, fluid temperature, part geometry, material properties, experimental conditions, or a combination of all or some of these factors. When dealing with composite materials the interactions between the fiber and the matrix are very difficult to predict accurately so typically specific numerical codes need to be developed to account for these effects.

Before taking the rather large step of developing a specialized FEA code for this project it is imperative to first study the process using existing commercial codes to determine the feasibility of these programs as they apply to the hydroforming process. Commercially available FEA codes do provide some distinct advantages over specialized codes. They are relatively easy to use and they provide an efficient method for establishing baseline data for comparison purposes. For the hydroforming of hemispherical cups, preliminary numerical modeling has been performed using the commercial code MARC.

5.1. Numerical Analysis Theory

The first step toward creating a finite element model for hydroforming was to determine the material properties that were needed to represent the composite sheets. Through a series of tensile tests the stress-strain plots, at different temperatures, for different types of composite sheets were created, Figures 15 - 17. This data was used as input into the model to provide the baseline material properties for the MARC model.

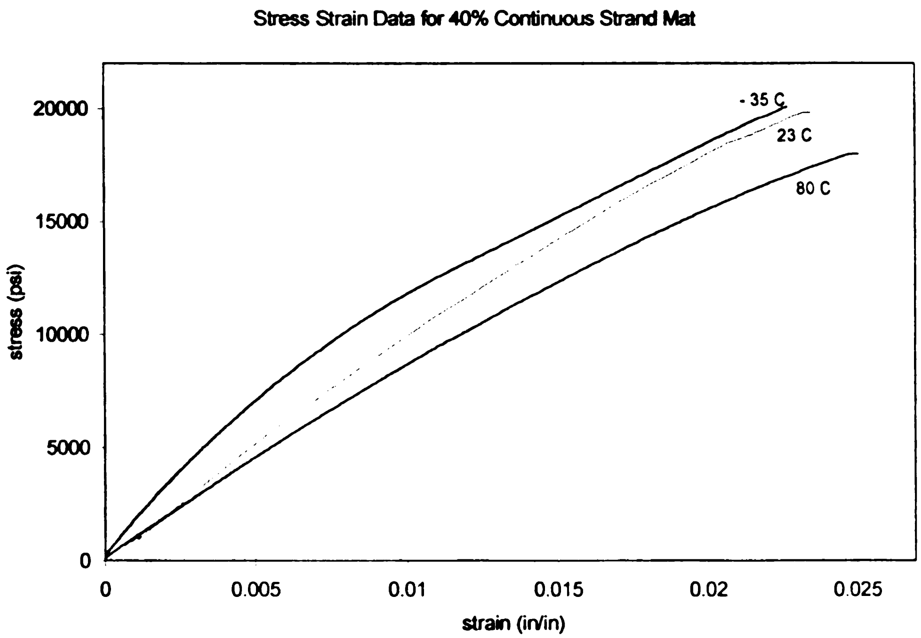

Figure 15. Stress-Strain plot for 40 % continuous strand mat, polypropylene matrix material.

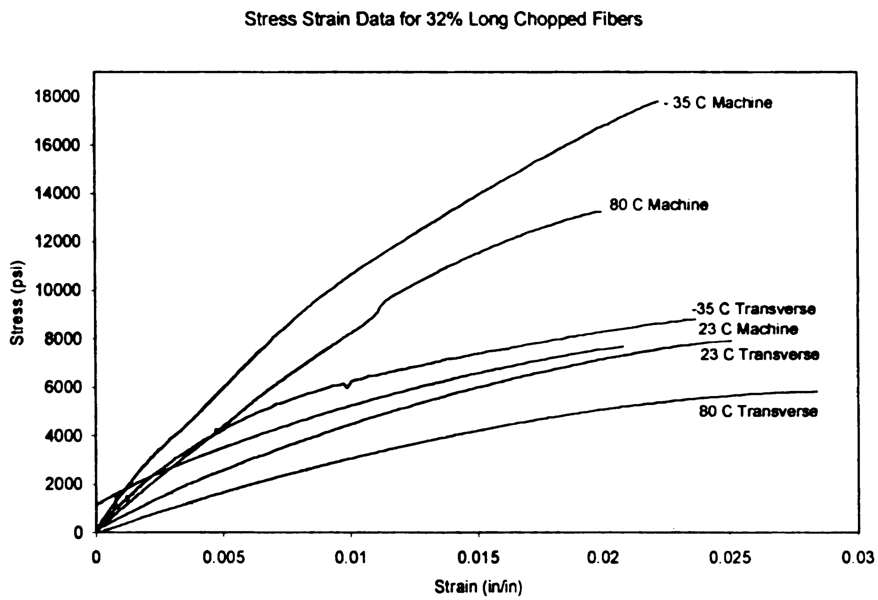

Figure 16. Stress-Strain plot for 32% oriented, long chopped fiber polypropylene matrix material.

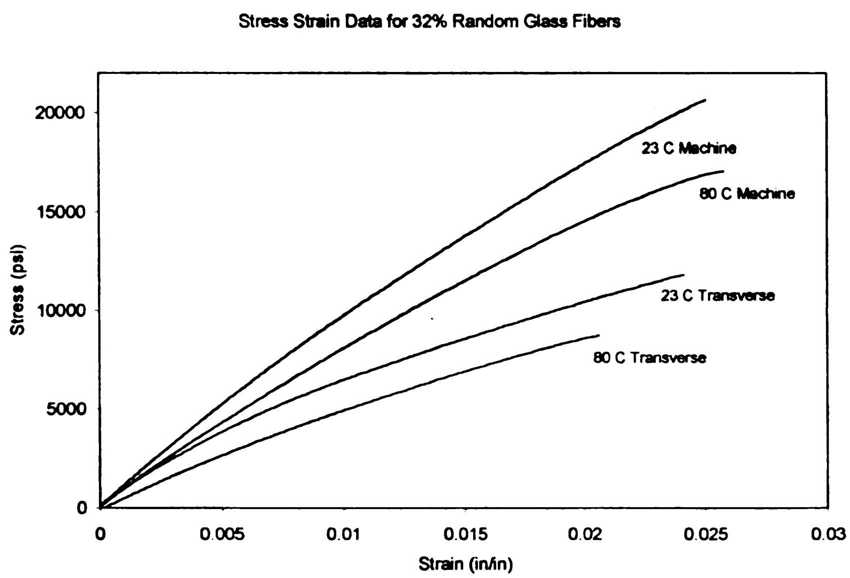

Figure 17. Stress-Strain plot for 32% random, long chopped fiber polypropylene matrix material.

Using MENTAT, the graphical input program for MARC, a three-dimensional graphical model of this process was created, see Figure 18. Initially the focus was placed on only modeling random fiber reinforced polypropylene matrix composite material formed into hemispherical cups. This allowed for some simplifying assumptions that eased the computational time and provided a general idea of whether the modeling procedure was valid.

Figure 18. Three-Dimensional model of the hydroforming process created using MARC.

The first assumption used to simplify the model was to assume that the work piece is isotropic. Since the initial modeling focused on a random fiber reinforced thermoplastic, this assumption was considered valid on the macroscopic scale. The second assumption that went into the modeling process was that the punch and die were treated as rigid and therefore did not deform during the process. Using these assumptions, and utilizing the material properties from the tensile tests, a much simpler, two-dimensional, axisymmetric finite element model of the hydroforming of composite material hemispherical cup process was created and is shown in Figure 19.

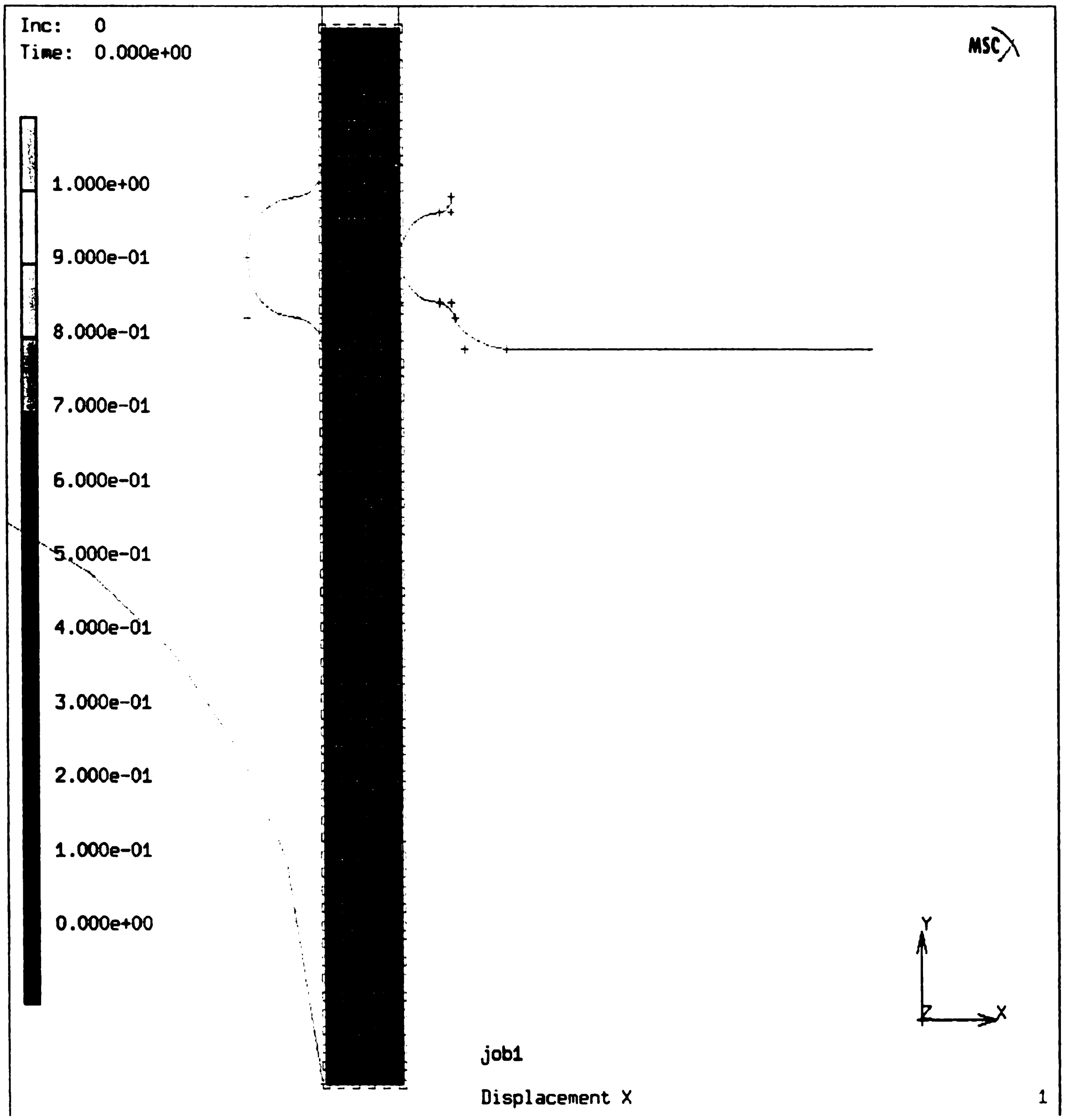

Figure 19. Two-Dimensional MARC model.

The model accounted for the contact analysis involving the clamping mechanism and the composite material work piece by modeling the opposing clamping draw bead halves as two rigid bodies, one static and one dynamic. This allowed the model to analyze the interactions between the composite material and the draw bead of the clamp as the clamping mechanism was closed.

Once the work piece was clamped, the dynamic rigid punch traveled to the material and began the deformation of the work piece. As this punch began to deform the material, a user-defined algorithm was utilized to simulate the changes in fluid pressure associated with the volume displacement in the pressure chamber. Utilizing an edge load that was placed on the surface of the material the fluid pressure within the chamber was numerically simulated. As the part deformed, this edge load stayed normal to the surface at all points thereby giving a fair representation of the fluid in the die cavity during the hydroforming operation.

The material deformation process was modeled using a rigid-plastic, incremental analysis that uses large displacements and an updated Lagrangian procedure. The modeling was conducted for a part that was drawn to depths varying from 1.5 to 3 inches (in) while varying the die cavity fluid pressures between 0 and 3000 pounds per square inch (psi). The boundary conditions utilized included the restriction of the y-direction movement of the lower end of the axisymmetric part to account for the axis of symmetry within the material. This allowed for a further simplification by analyzing only half of the workpiece and assuming symmetric behavior of the overall part.

Two basic failure criteria were considered for this analysis; equivalent von Mises stress and total equivalent plastic strain. The yield stress of a material is a measured stress level that separates the elastic and inelastic behavior of the material. The magnitude of the yield stress is generally obtained from a uniaxial test. However, the stresses in a structure are usually multiaxial. A measurement of yielding for the multiaxial state of stress is called the yield condition. Depending on how the multiaxial state of stress is represented, there can be many forms of yield conditions. For example, the yield condition can be dependent on all stress components, on shear components only, or on hydrostatic stress.

Although many forms of yield conditions are available, the von Mises criterion is the most widely used, and was the criterion selected for the numerical analysis of the composite hemispherical cups hydroforming process. The success of the von Mises criterion is due to the continuous nature of the function that defines this criterion and its agreement with observed behavior for the commonly encountered ductile materials [33]. The von Mises criterion states that yield occurs when the effective (or equivalent) stress (σ) equals the yield stress (σ_y) as measured in a uniaxial test. Figure 20 shows the von Mises yield surface in two-dimensional stress space.

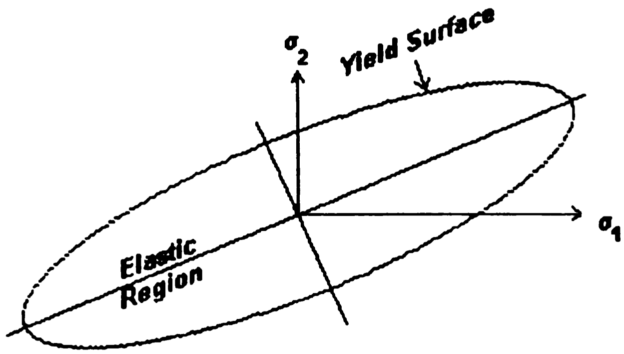

Figure 20. von Mises yield surface in two-dimensional stress space.

Mathematically, for an isotropic material, the von Mises yield criterion is defined in equation 1,

$$\bar{\sigma} = \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{1/2} / \sqrt{2} \qquad (1)$$

where σ_1, σ_2, and σ_3 are the principal Cauchy stresses.

$\bar{\sigma}$ can also be expressed in terms of non-principal Cauchy stresses as illustrated in equation 2.

$$\bar{\sigma} = [(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)]^{1/2} / \sqrt{2} \qquad (2)$$

The yield condition can also be expressed in terms of the deviatoric stresses as shown in equation 3.

$$\bar{\sigma} = \sqrt{\frac{3}{2}\sigma'_{ij}\sigma'_{ij}} \quad (3)$$

Where σ'_{ij} is the deviatoric Cauchy stress expressed as shown in equation 4.

$$\sigma'_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij} \quad (4)$$

Total equivalent plastic strain refers to the ability to relate multiaxial strain increments to an equivalent increment in a uniaxial tensile test. Setting the one-dimensional plastic work equal to the plastic work done in a general state allows for the definition of an equivalent or effective strain increment, d $\bar{\varepsilon}$, as illustrated in equation 5 (principle of equivalent plastic work) [32].

$$\bar{\sigma}d\bar{\varepsilon} = \sigma_{ij}d\varepsilon_{ij} = \sigma_i d\varepsilon_i = \sigma_1 d\varepsilon_1 + \sigma_2 d\varepsilon_2 + \sigma_3 d\varepsilon_3 \quad (5)$$

Where $\bar{\sigma}$ is the effective stress, σ_i is the stress increment and ε_i is the strain increment.

For the initial evaluations, the strain criterion was based on the results of a simple power law equation fit to the stress strain curves (Figure 17). This resulted in the expression in equation 6.

$$\sigma = 564790\varepsilon^{0.9056} \quad (6)$$

Equation 6 is in the form of the basic Hollomon equation, $\sigma = k\varepsilon^n$, where k is the strength coefficient and n is the work hardening rate. As a baseline

approximation for the strain failure criteria, the Considere criterion was used resulting in a strain failure criteria of $\varepsilon = n$ or $\varepsilon = 0.90$. Even though this criterion is typically only applied to metallic materials, it can be equally applied to polymer materials.

There are two physical factors that must be considered when applying this criterion to polymeric material. First is that the dissipation of mechanical energy as heat in the necking region. This can raise the temperature of the material, which can cause significant softening, as the strain-rate increases, so will the softening effect. The second factor to be considered is the deformation resistance at the necking region. At this region of the forming material the strain rate is higher than in the surrounding material. Therefore, depending on the strain-rate dependence of the yield stress, the deformation resistance in this region can increase [7].

The importance of these two opposing physical factors will depend upon the length of the necking region of the draw blank material as well as the thickness of the material and the strain rate of the hydroforming process. Based on these limitations, the use of the Considere criterion, while not an ideal choice for the polymeric material, will provide a starting point for the evaluation and will be modified as the correlation between the experimental and numerical procedure progresses.

5.2. Numerical Analysis Results

Overall the model showed results that were qualitatively consistent with the experimental findings. To better illustrate the observations made about the results it is important to establish a frame of reference. For the purpose of this discussion the final shaped hemispherical part has been split into three distinct regions as illustrated in Figure 21. Zone I represents the draw bead area of the hydroformed part, Zone II is the area of the part that forms against the sidewall of the pressure cavity entrance, and Zone III represents the dome of the hemispherical part being formed.

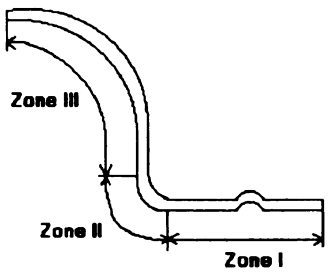

Figure 21. Zoned regions of the shaped hemispherical cups to be used in the discussion.

Figure 22 illustrates the model for a part that has been drawn to a depth of 3 in. Figures 23 through 26 illustrate the changes in von Mises stresses for fluid pressures of 0, 1000, 2000 and 3000 psi, drawn to a depth of 1.5 inches. Figures 27 through 30 illustrate the changes in total equivalent strains for the same fluid pressure changes and draw depth. The 1.5 inch depth was chosen to correspond with the depth that the material ruptured during the experiments in the absence of an applied fluid pressure. This depth allowed for a direct comparison between the numerical and experimental stress and strain values to determine the correlation between the two experimental and numerical analyses.

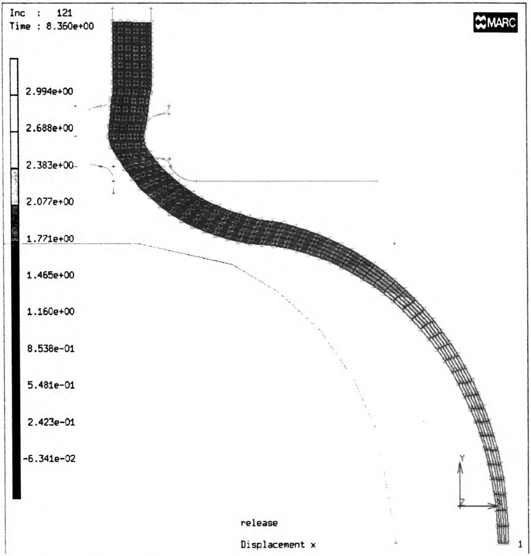

Figure 22. MARC model displacement results, depth of 3 inches.

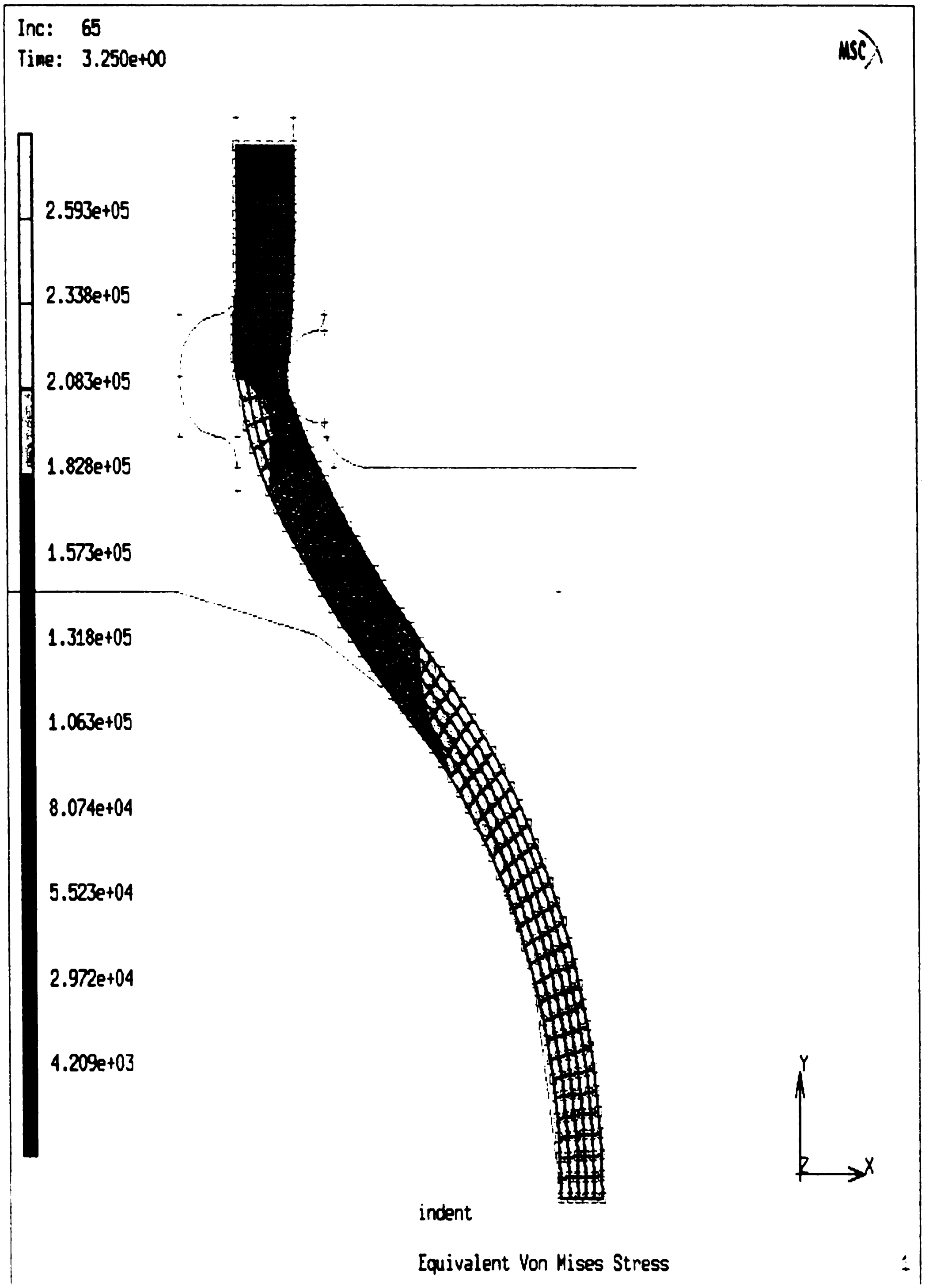

Figure 23. von Mises stress MARC model results, fluid pressure of 0 psi.

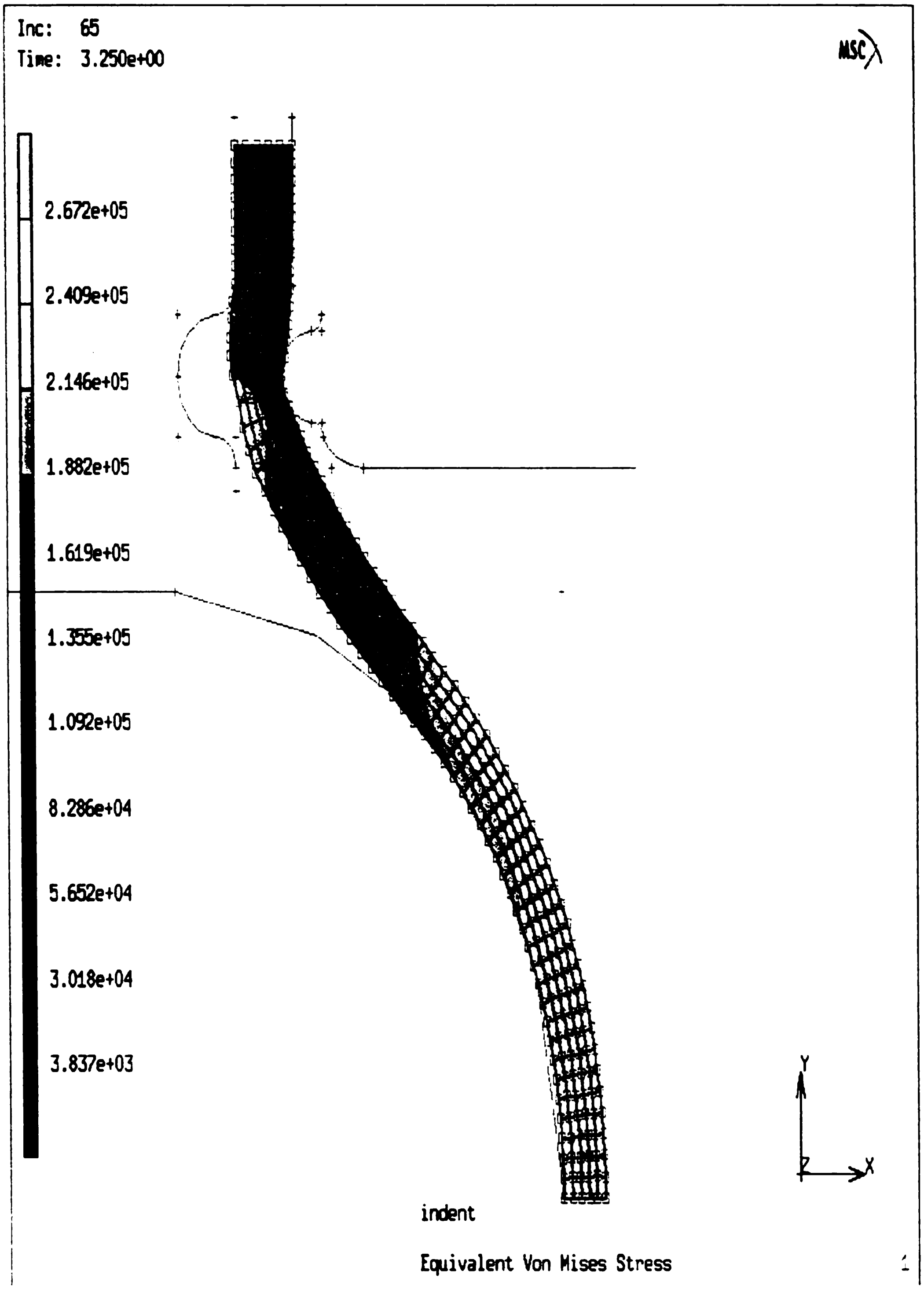

Figure 24. von Mises stress MARC model results, fluid pressure of 1000 psi.

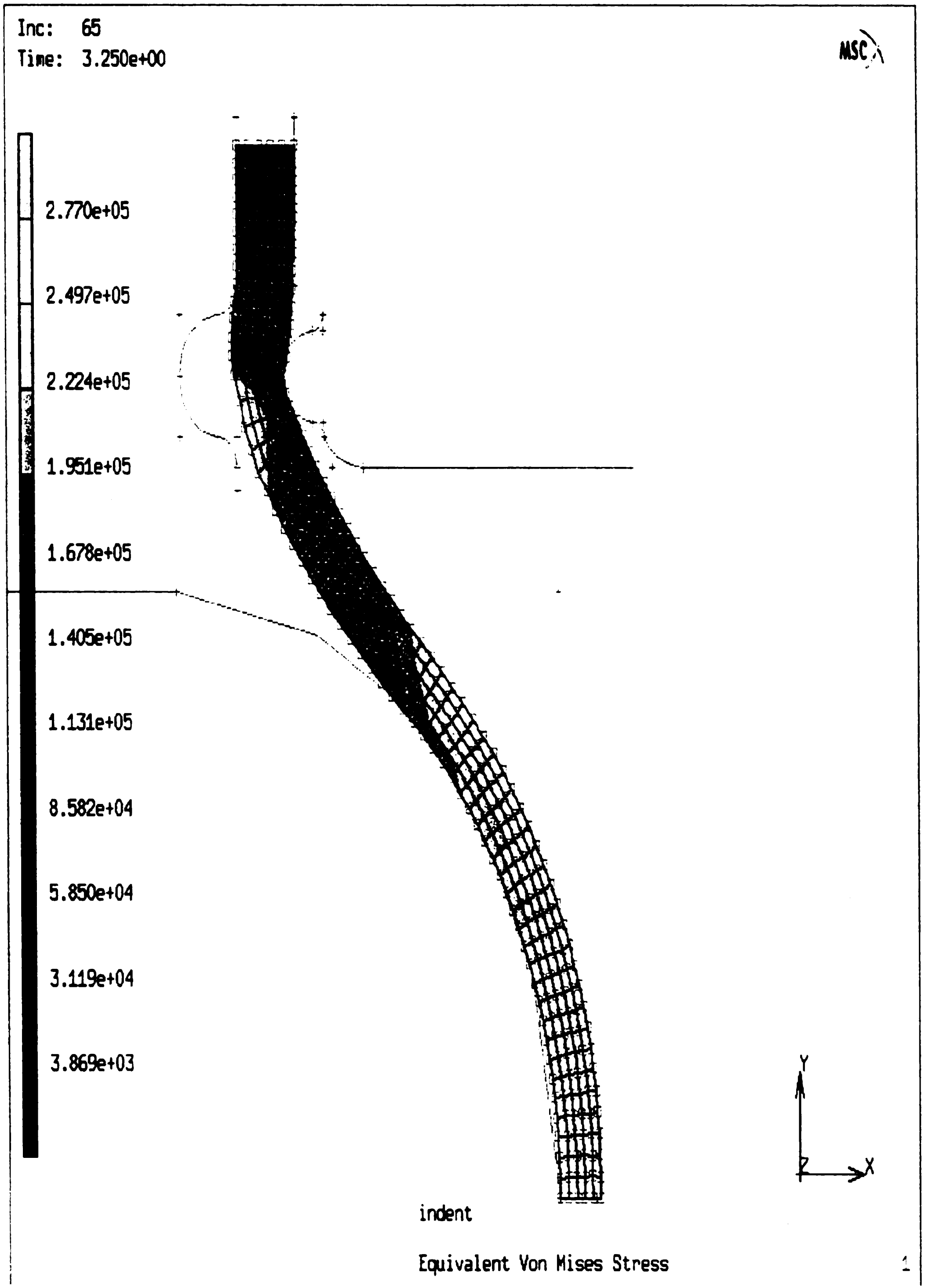

Figure 25. von Mises stress MARC model results, fluid pressure of 2000 psi.

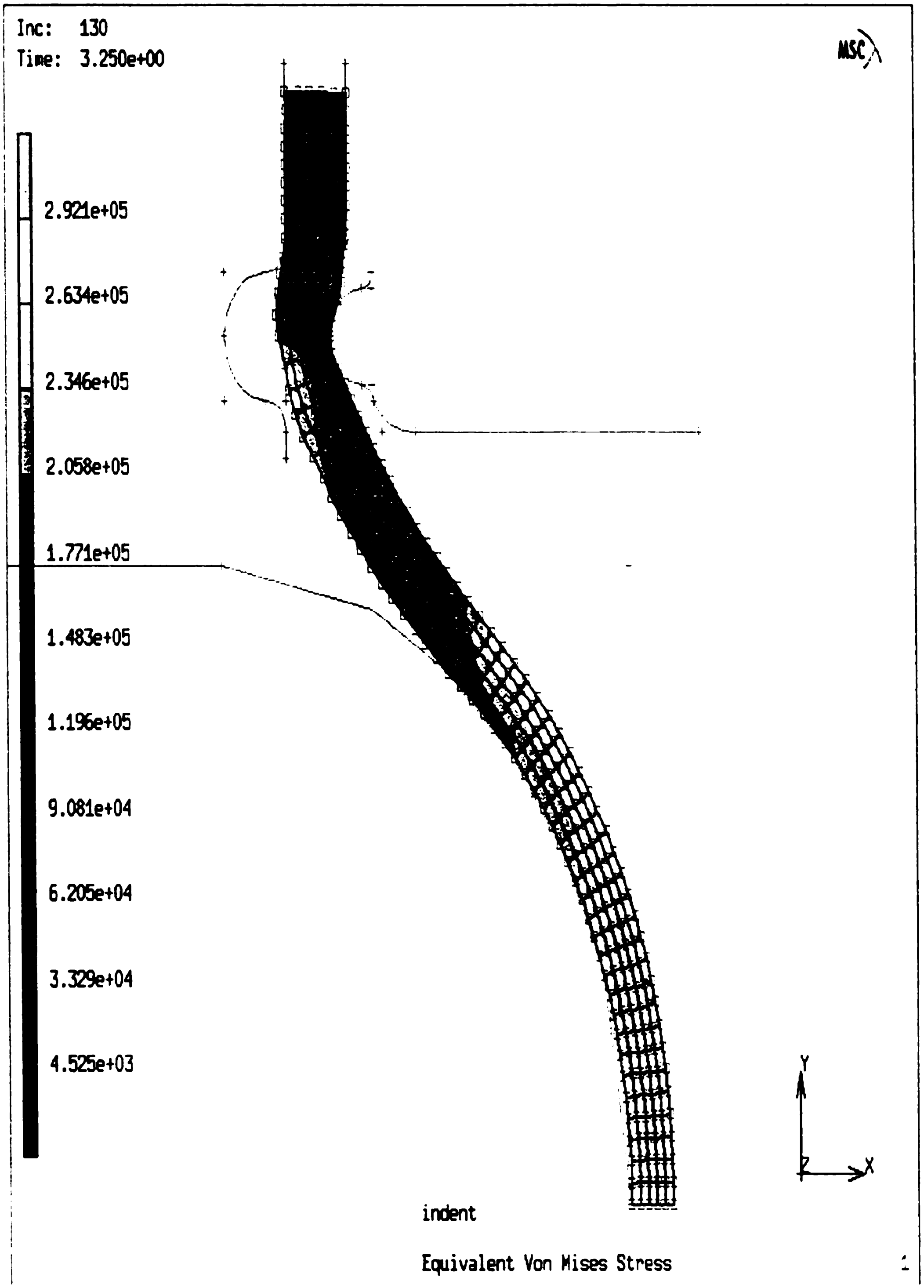

Figure 26. von Mises stress MARC model results, fluid pressure of 3000 psi.

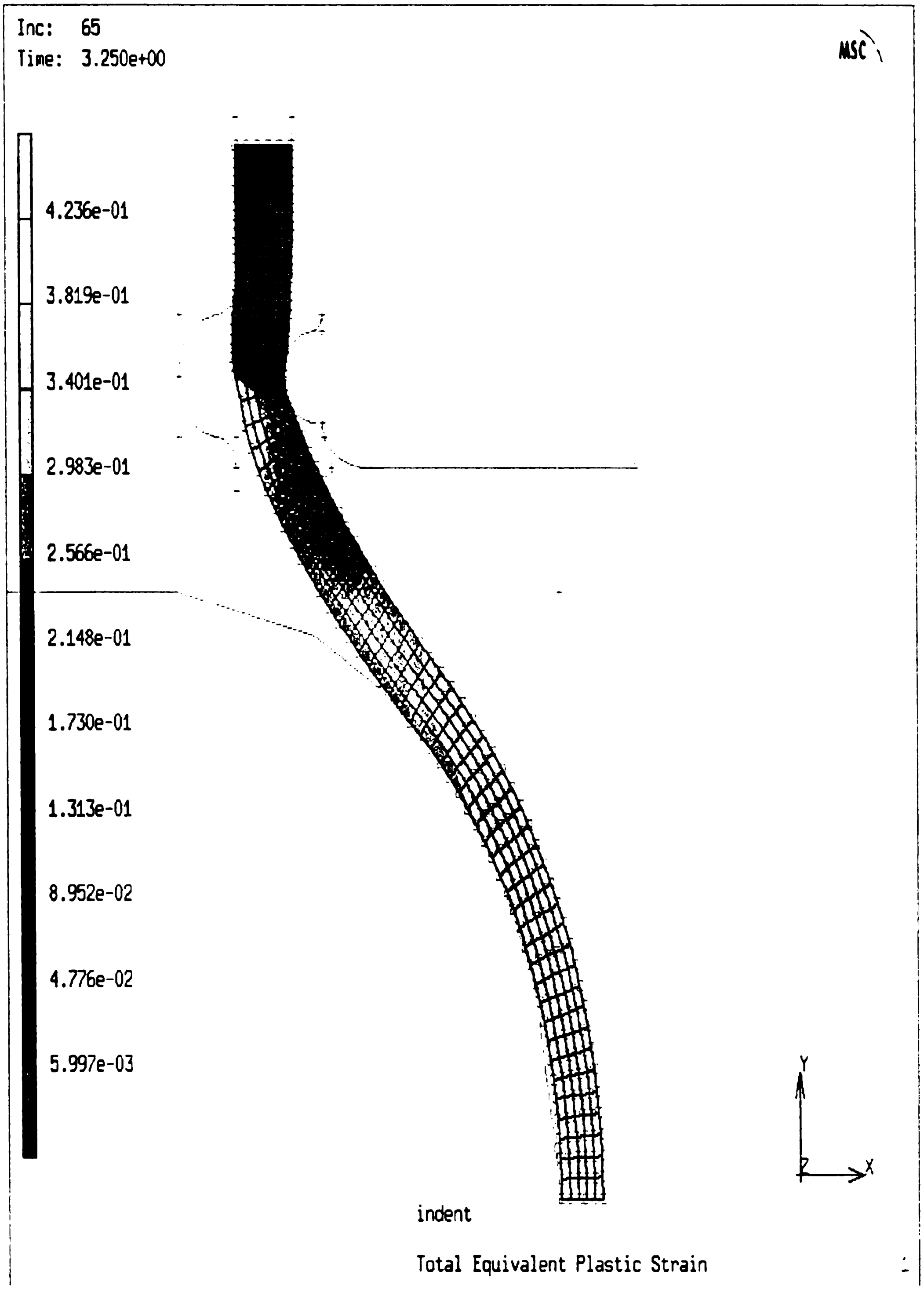

Figure 27. Total equivalent strain MARC model results, 0 psi fluid pressure.

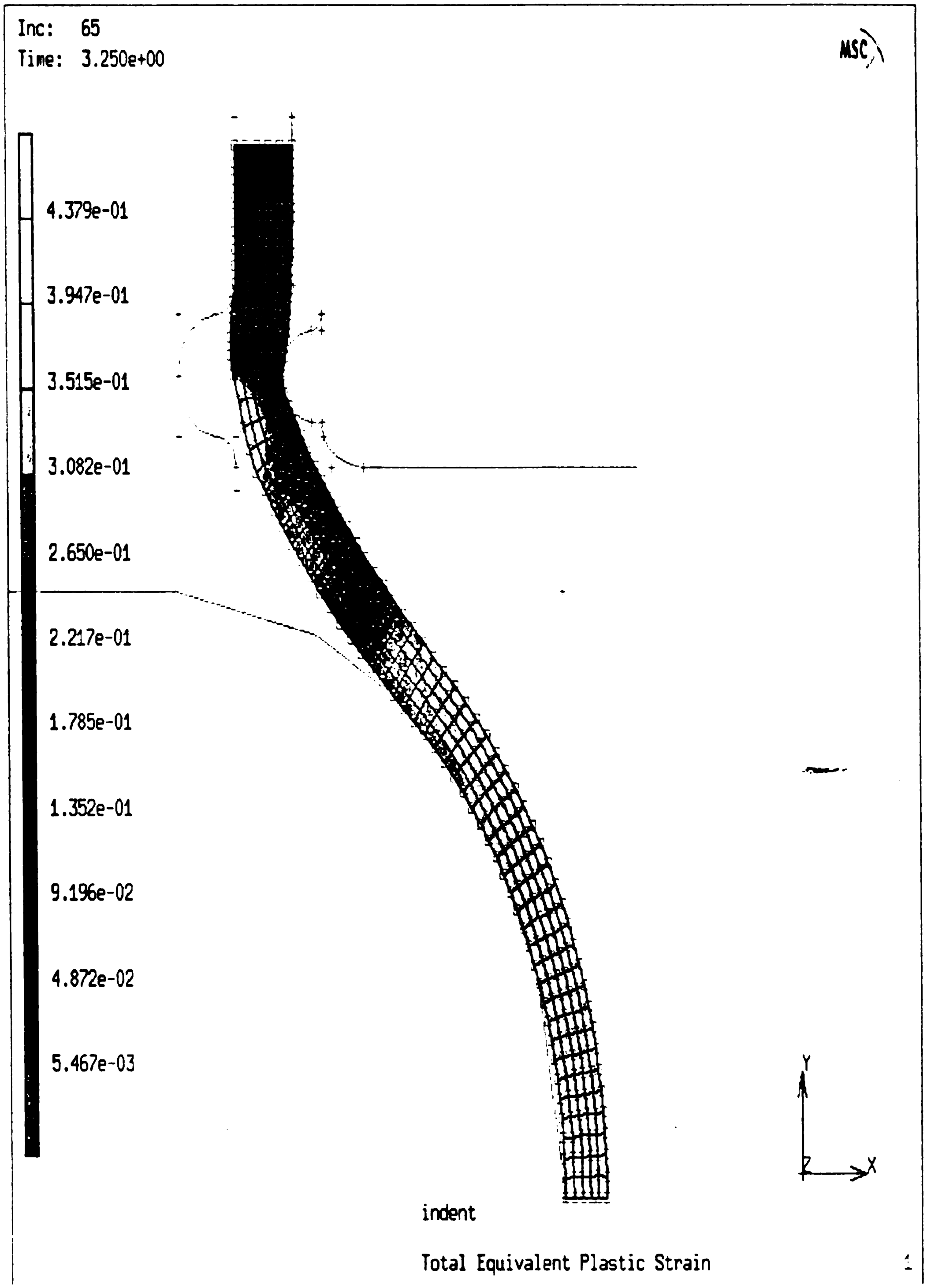

Figure 28. Total equivalent strain MARC model results, 1000 psi fluid pressure.

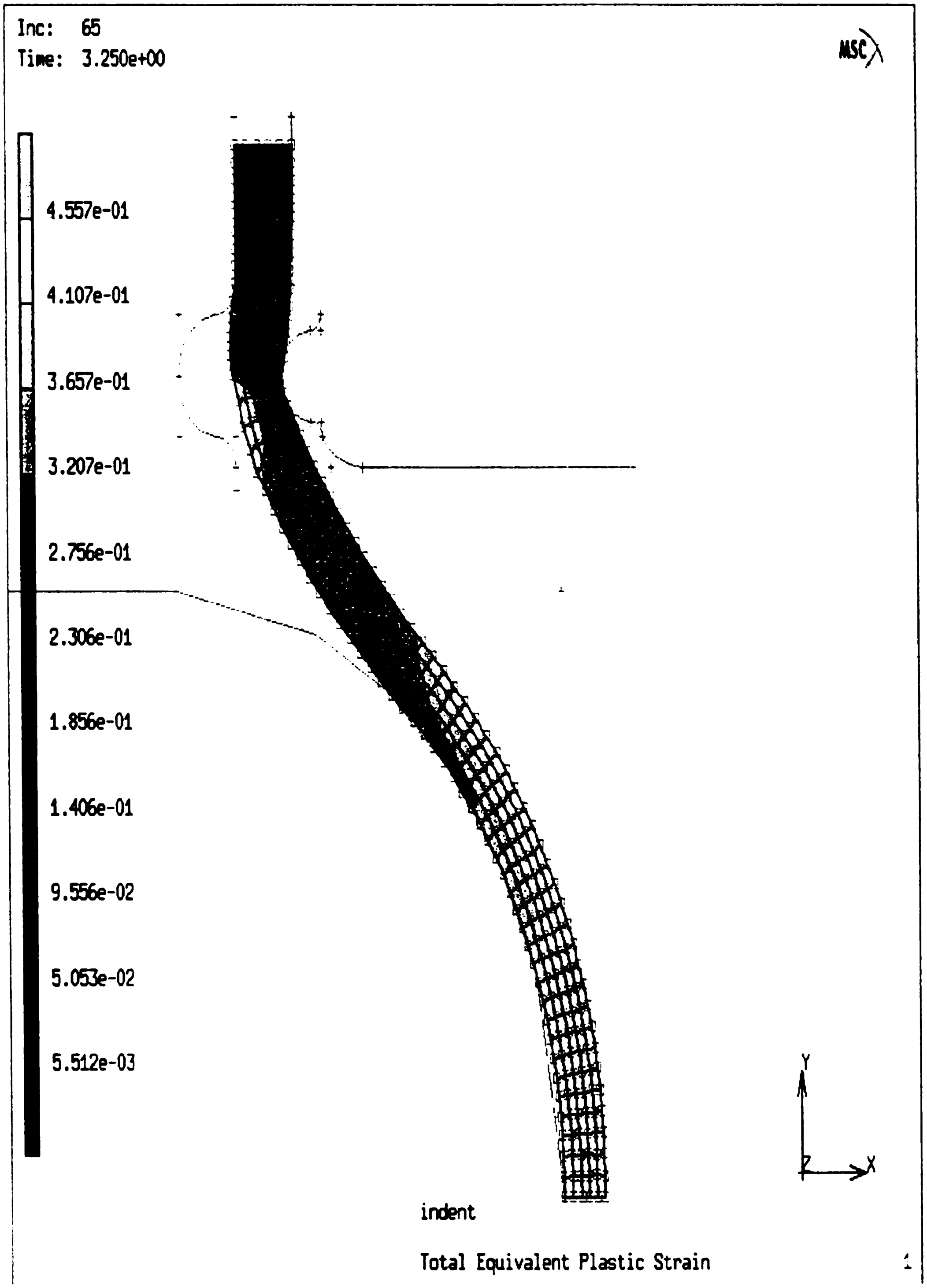

Figure 29. Total equivalent strain MARC model results, 2000 psi fluid pressure.

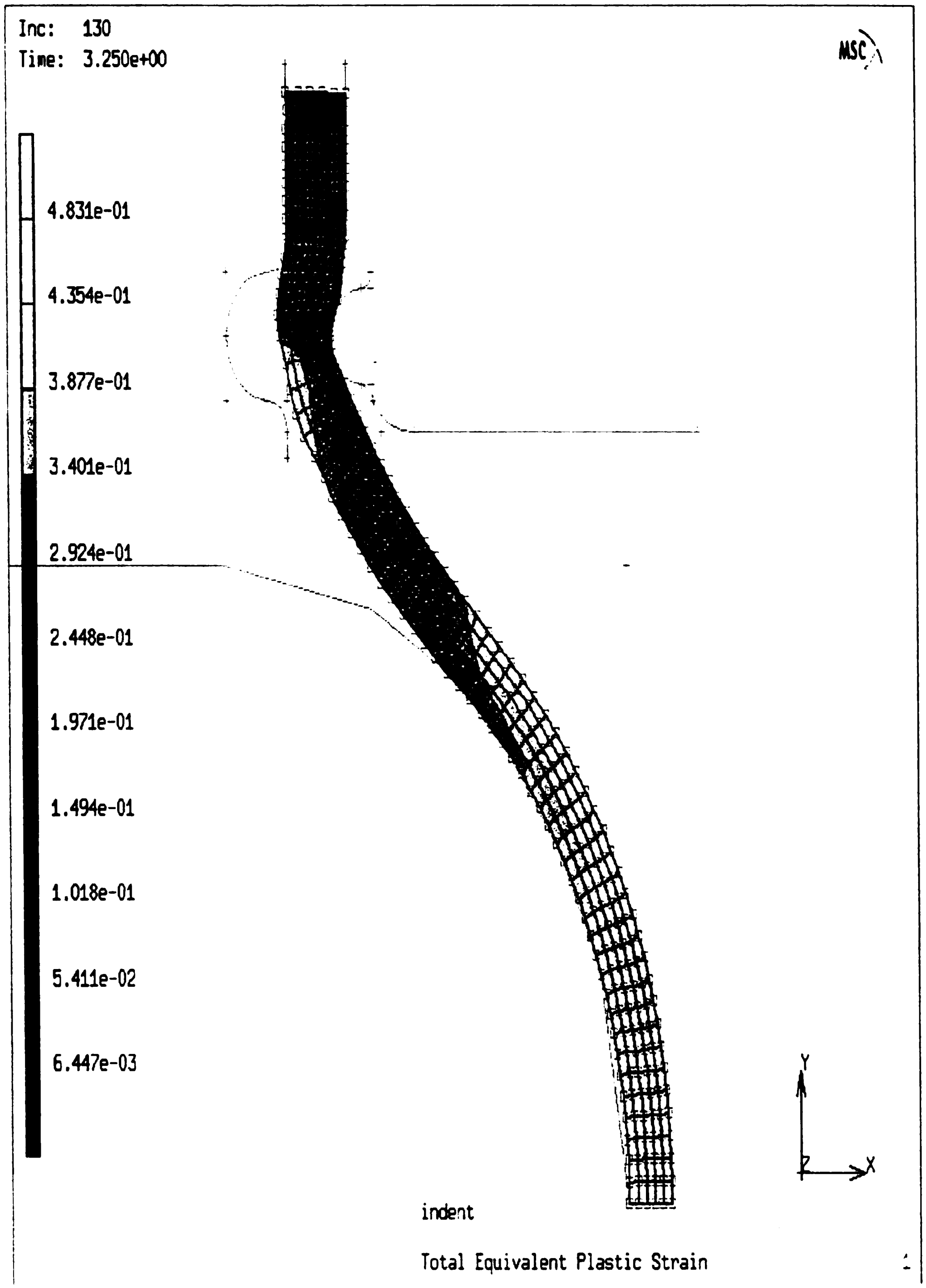

Figure 30. Total equivalent strain MARC model results, 3000 psi fluid pressure.

Figures 31 and 32 represent a cumulative plot of the von Mises stresses plotted versus displacement for the varying fluid pressures. Figures 33 and 34 illustrate the total equivalent strains plotted versus displacement also or the varying fluid pressures. The second plot of each series is just an expanded portion of the first plot illustrating in greater detail the trends that have been exhibited by the model.

Through a comparison of the results from Figures 31 and 32 to the expected stress failure criteria of 137 megapascals (MPa) a discrepancy between the model and the experimental results was illustrated. The numerical analysis showed stress results at the 1.5 inch experimental draw depth failure that was an order of magnitude higher than the yield stress of the material. The numerical results illustrated in Figures 33 and 34 showed that predicted strain failure criteria of 90% strain was not achieved until a draw depth that was well above 2 inches. Again, this result did not correlate with the results found through the experiments.

These discrepancies could be attributed to the work hardening model that was used for the numerical analysis. The initial work hardening model was based on uniaxial stress-strain data and was used as a baseline to start the numerical analysis. The initial uniaxial data (Figure 17) corresponded to material that was tested at two different temperatures, both below the forming temperature of the material. The stress-strain behavior of the material at, or above, the forming temperature was not a priori available so the work hardening model used for the numerical analysis had to be modified based on observations about the nature of the equation and trial and error methods.

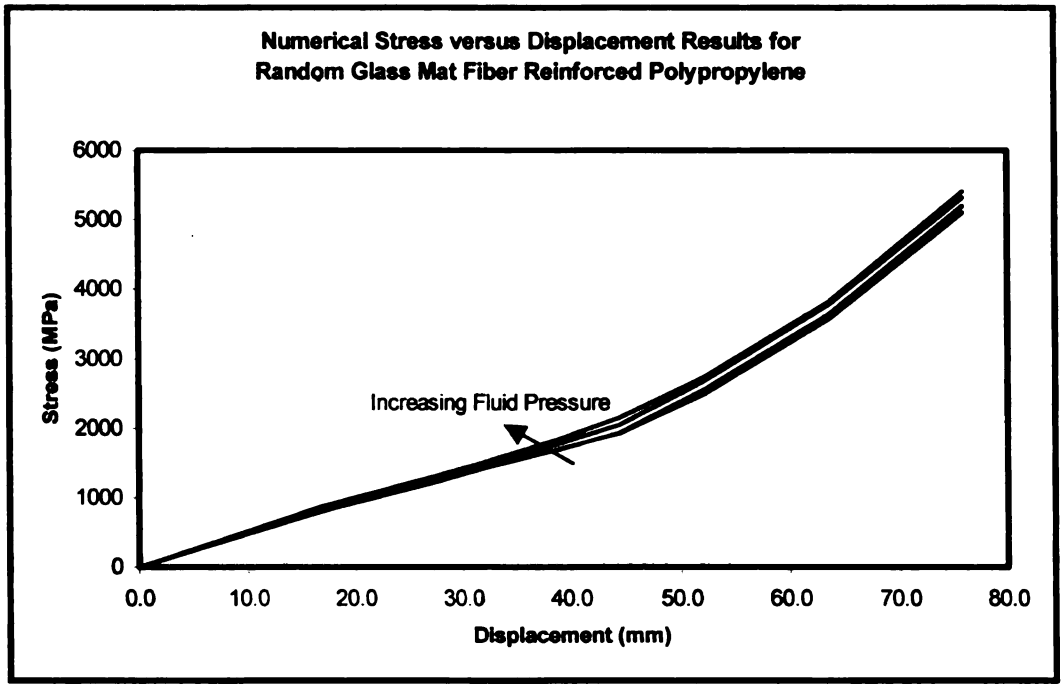

Figure 31. Plot of von Mises stress versus displacement for fluid pressures of 0, 1000, 2000, and 3000 psi.

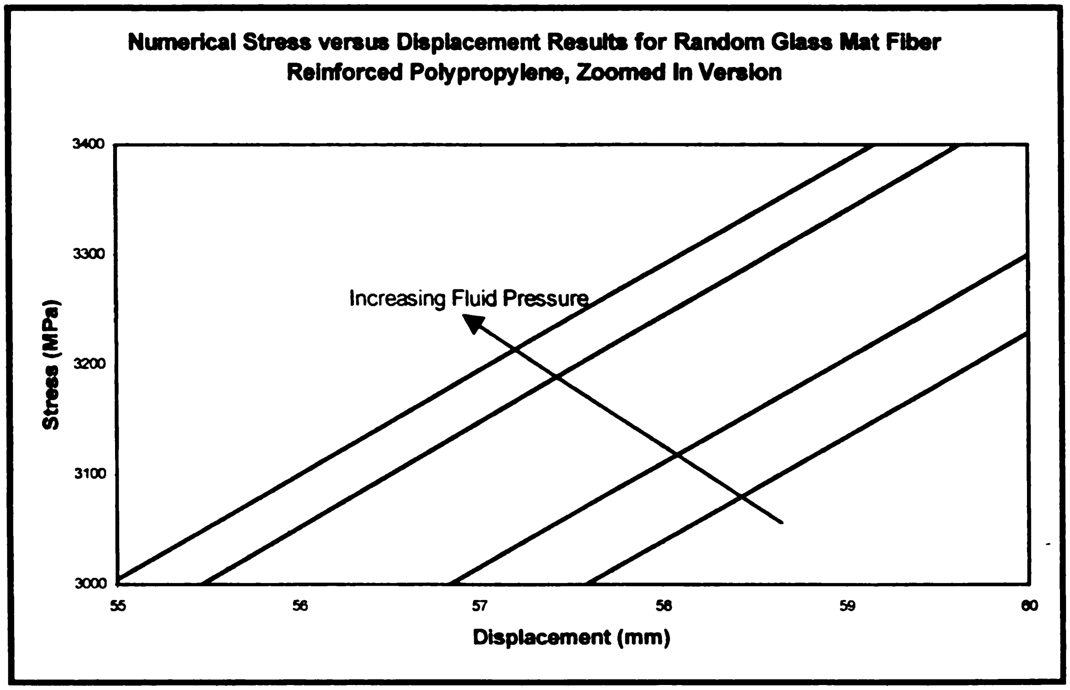

Figure 32. Enhanced plot of von Mises stress versus displacement for fluid pressures of 0, 1000, 2000, and 3000 psi.

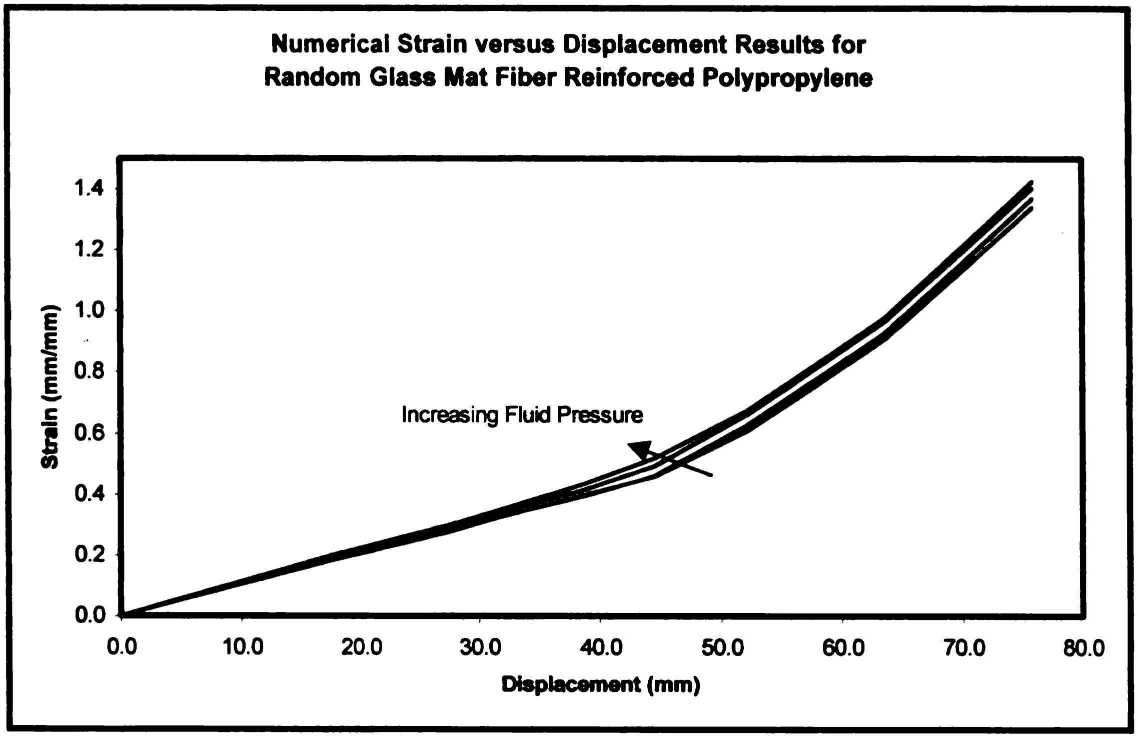

Figure 33. Plot of total equivalent plastic strain versus displacement for fluid pressures of 0, 1000, 2000, and 3000 psi.

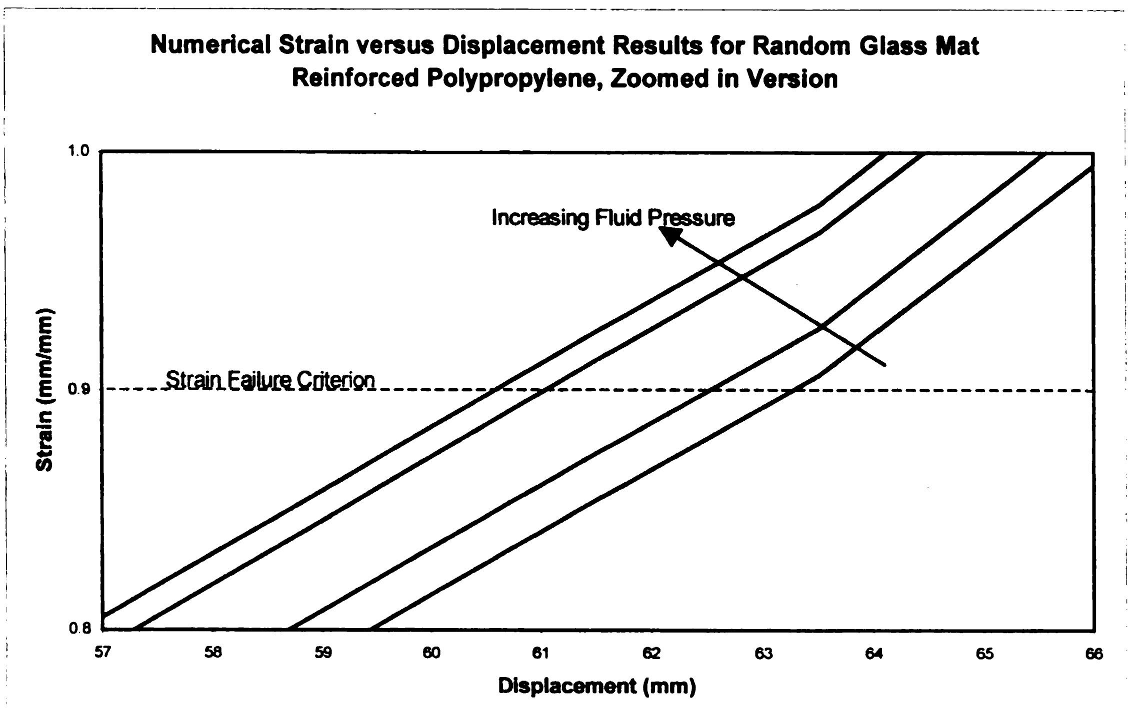

Figure 34. Enhanced plot of total equivalent strain versus displacement for fluid pressures of 0, 1000, 2000, and 3000 psi.

The first modification that was made to the work hardening model was simply reducing the strength coefficient, k, by an order of magnitude from 564790 to 56479 while keeping the work hardening rate, n, the same at 0.9, therefore the new work hardening model became $\sigma = 56479\varepsilon^{0.9}$. The numerical analysis was performed under the same conditions as the previous trials with one change. Since the k value had been reduced by an order of magnitude, the same order of magnitude change had to be incorporated into the fluid pressures to ensure an accurate comparison between the two models. Therefore, the new numerical analysis was conducted using fluid pressures of 0, 100, 200 and 300 psi. Figures 35 and 36 graphically illustrate the numerical stress results for that were achieved through the use of the new material model whereas Figures 37 and 38 represent the strain results.

As shown in Figures 35 and 36 very good correlation between the numerical and experimental results was achieved through the use of the new work hardening model. The numerical model showed stress values on the order of 137 MPa at the 34 mm draw depth corresponding to experimental material failure. The same trend noted earlier was also found in this model, as the fluid pressure in the chamber was increased the part failed at shallower draw depths.

A new strain failure criterion of approximately 37% was determined by correlating the experimental failure draw depth to the numerical strain data illustrated in Figures 37 and 38. This is well below the 90% strain predicted by the Considere criterion but the question still remains as to the accuracy of this value. Based on a pure bending analysis of the material the strain failure should be at approximately 8%. From the uniaxial stress-strain data (Figure 17) the material should fail at a strain of approximately 2.5%. Which value was most accurate and representative of the material still remained.

Through a careful examination of the 37% strain and what the value represented it was suggested that the modified strain value might not be too far off. For the random fiber material the glass reinforcement was not continuous so as the material was deformed a glass fiber may have broken due to either stress or strain failure but that the failure of one fiber did not imply failure of the overall material. The polypropylene matrix of the material had a strain failure criteria that ranged anywhere from 25 – 600% strain depending on the temperature of the material and the method used to manufacture the composite. Therefore it was suggested that the fiber might have broken at lower strain values but that the matrix material may not have reach strain failure thereby leading to the higher strain values shown by the model.

When increasing the fluid pressure in the die cavity, the expected result was the ability to draw the part to a deeper depth before failure. The model was not able to confirm this expected result but the modeling results were consistent with the experimental results. As the fluid pressure increased, it caused the material to sag and added a tension to the material, especially at the interface between

Zones II and III. This increased tension led to the premature failure of the material.

The second factor associated with this increased pressure was the reverse bending effect. As mentioned in the experimental section of this report, the material was unsupported at the locations where the punch was not in contact with the material. As the punch began to deform the material the decrease in volume led to an increase in pressure. This increased fluid pressure acted upon the unsupported regions by forcing the material downward. As the bent material came into contact with the punch the material was then forced to reverse direction and began moving upwards. This direction reversal led to an increased amount of stress being imparted to the material and coincided with the location of the premature material failures. As expected, as the fluid pressure was increased from 0 to 3000 psi, the draw depth of the hemispherical part decreased yet the location of the failure remained consistent, at the interface between Zones II and III.

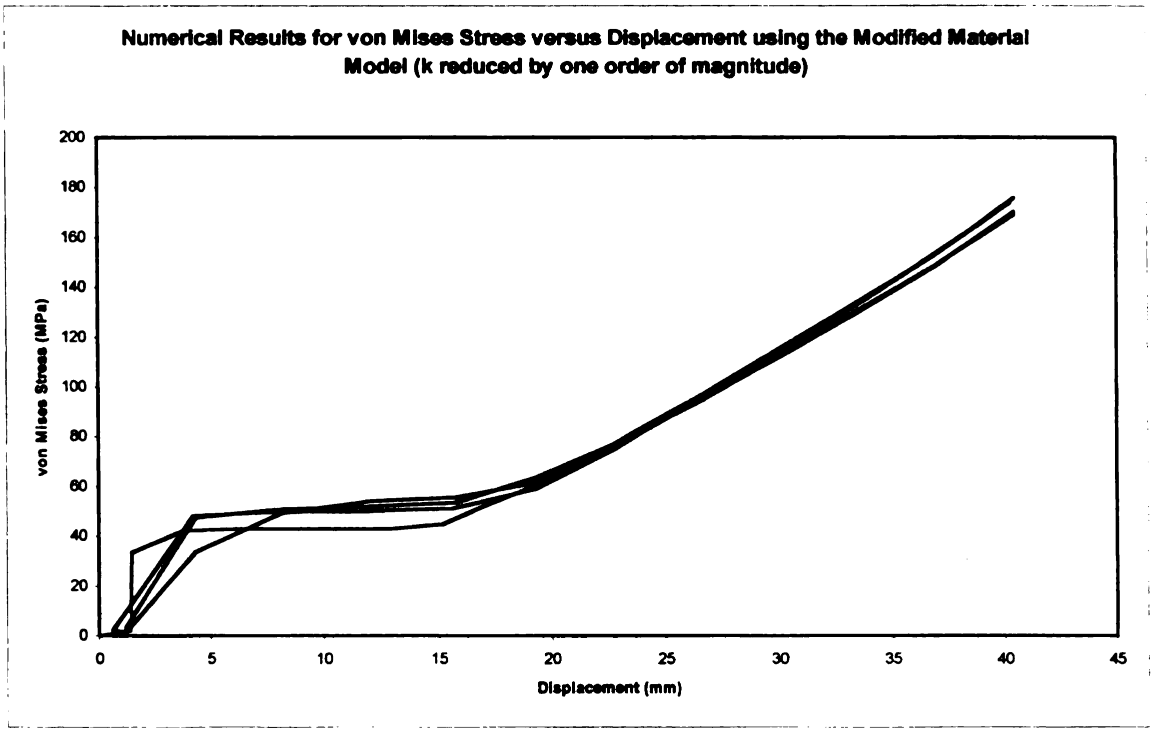

Figure 35. Plot of von Mises stress versus displacement for fluid pressures of 0, 100, 200, and 300 psi using the modified work hardening model.

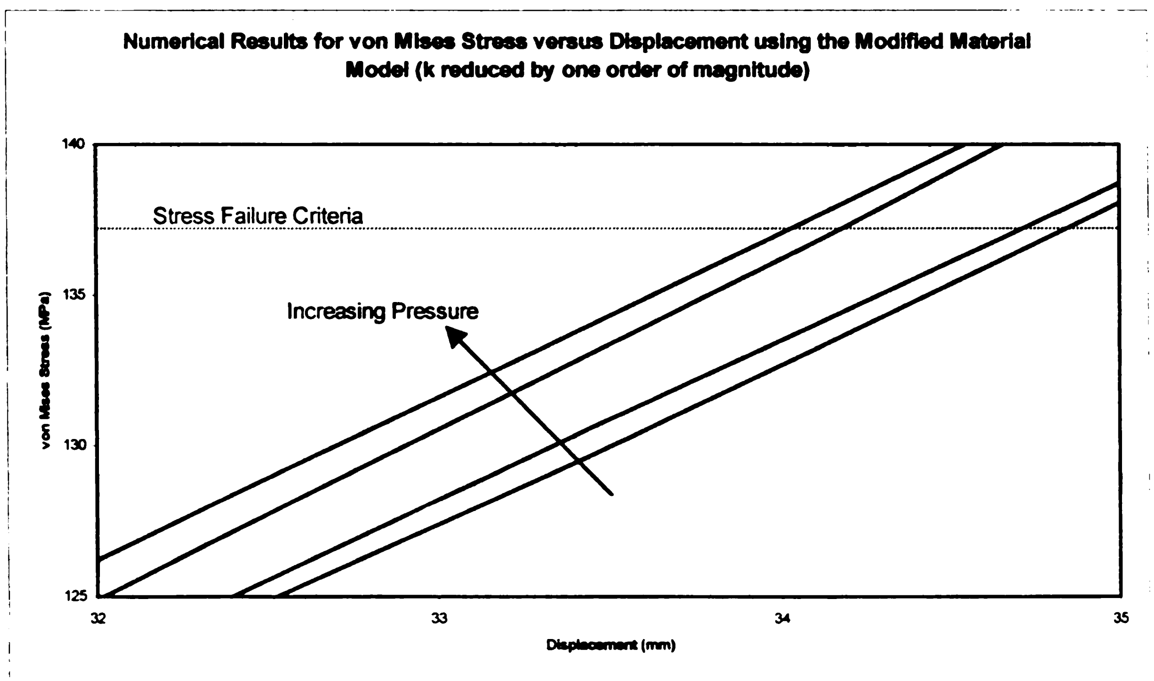

Figure 36. Enhanced plot of von Mises stress versus displacement for fluid pressures of 0, 100, 200, and 300 psi using the modified work hardening model.

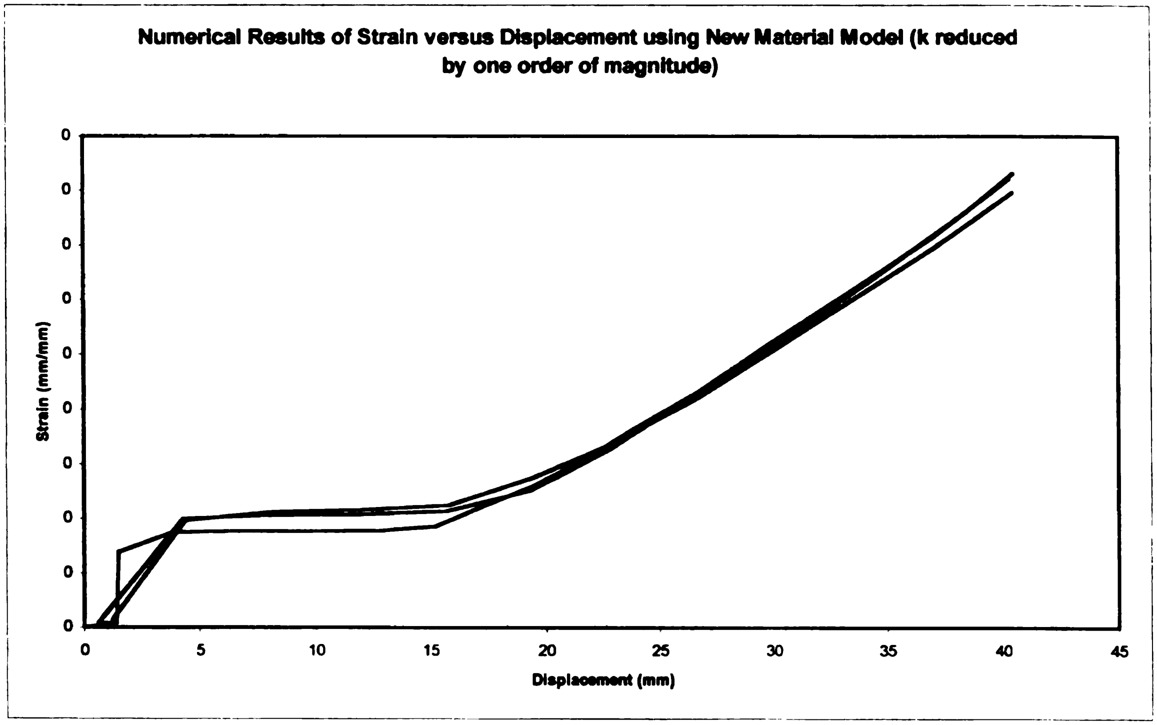

Figure 37. Plot of strain versus displacement for fluid pressures of 0, 100, 200, and 300 psi using the modified work hardening model.

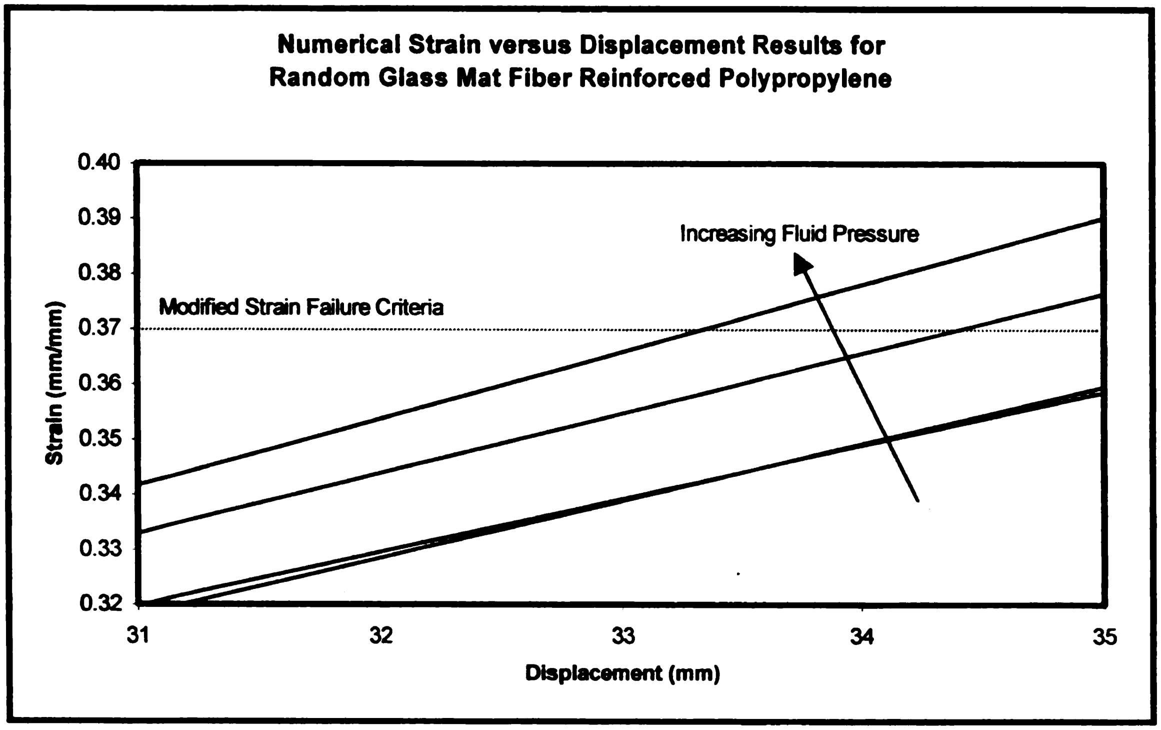

Figure 38. Enhanced plot of strain versus displacement for fluid pressures of 0, 100, 200, and 300 psi using the modified work hardening model.

When evaluating the part from a strain failure perspective the same trends were found. As the fluid pressure within the die cavity was increased the material was found to exhibit premature failure. This trend was consistent with the experimental data and can be attributed to the same factors associated with the premature stress failures.

Another advantage that was expected during the hydroforming process was the ability of the pressure to force the material onto the punch when working with higher fluid pressures. This would allow for better shaping of the final part in addition to aiding in the decrease of one of the high stress concentration areas typically found in these types of parts. Traditionally a high stress concentration was found in Zone II due to the contact between the material and the leading edge of the die cavity. By utilizing the fluid pressure the material in this area was forced to conform to the punch and was prevented from coming into contact with the die cavity surface. So far the modeling results are inconclusive in regard to the uniform thinning that was anticipated. Once the model is modified to account for an equalizing pressure on the punch side of the material the uniform thinning should be readily apparent.

Chapter 6

FUTURE WORK

The initial experimentation and numerical analysis did not provide the results that were expected but the correlation between the two was very similar. The use of the thin diaphragm material illustrated the benefits of an applied hydrostatic pressure so the process needs to be redesigned to take advantage of this benefit. There are a series of steps that will be outlined for both the experimental and numerical portion of this research in an attempt to further along the research goal of the verification of the stamp hydroforming method as a viable alternative to traditional composite processing methods.

6.1. Future Experimental Work

As mentioned earlier, the main obstacle that has arisen during the experimental phase of this research is material sag during the initial material deformation/chamber volume displacement operation (Figure 13). This material sag is leading to an increase in the tension within the material and is leading to premature rupture of the material. A new design has been created and is currently being built that may alleviate this complication.

The new design, illustrated in Figure 39, fills the bottom chamber with fluid that is equalized with the fluid in the upper chamber. As the pressure in the upper fluid chamber increases due to the volume change, the displaced fluid will be forced into the bottom chamber thereby equalizing the pressure between the chambers. This will allow for the support of the material that is not in contact with the punch and will prevent the material from sagging in these regions. In addition, the material that is in contact with the punch will experience a pressure that is representative of the stiff material induced localized hydrostatic pressure that was shown to give a deeper draw prior to material failure.

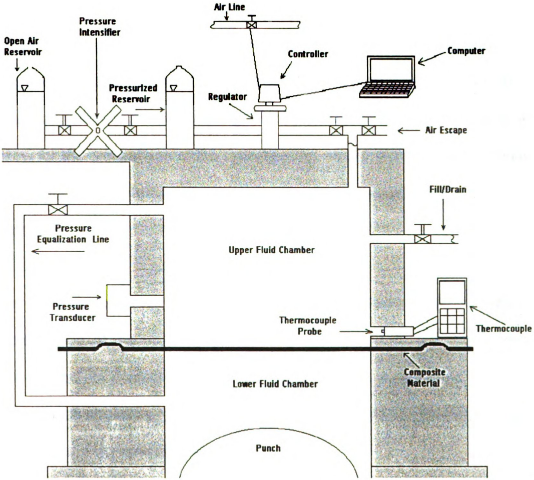

Figure 39. Schematic of the newly designed die that will alleviate the material sag complication associated with the current experimental set-up [31].

A valve is placed on the equalization line that will allow for the interruption of the fluid flow to the lower chamber. This will be used near the end of the cycle when additional pressure is required to ensure that the material conforms adequately to the shape of the punch. Using the new design the process will be reevaluated and optimized with regard to rupturing instabilities.

Once the process has been optimized for rupturing, it is important to initiate an evaluation of the wrinkling effects during the hydroforming process. This can be accomplished by studying hydroforming with an elliptical punch. Due to the nonsymmetrical nature of the ellipse this geometry provides a great opportunity to study the wrinkling effects on the thermoplastic material as it is formed. Again, the elliptical punch is a widely used geometry for studying wrinkling effects and will allow for the comparison of the hydroforming results to the existing wrinkling data for other thermoplastic composite shaping methods such as thermoforming and stamping.

The experimental study of hydroforming with an elliptical punch will allow for the optimization of the processing methods, this time with regard to wrinkling effects. Used in conjunction with the rupturing optimization an ideal fluid pressure-punch stroke path from Figure 11 should be determined and will lead to the next step of the experimentation process.

This next step will be to study the effects of simultaneous wrinkling and tearing during the hydroforming process. This type of experimentation could be accomplished by using a tapered square cup or some other readily accepted geometry. Using the already determined optimized pressure and temperature data from the prior experiments the new experiment can be run and the results can be optimized once again.

This will lead to the final optimization and should lead to the experimental process being readied for implementation in industry by demonstrating the advantages that hydroforming has over the traditional composite forming methods. Advantages that include the cost savings associated with the elimination of the female die and the ability to shape parts that have more uniformity, deeper drawing and minimal thinning in the draw-in area of the part.

Once the advantages of the hydroforming process have been verified for the glass mat fiber reinforced polypropylene thermoplastic materials, experimentation can be performed for other types of materials. Thermoplastics such as polyethylene, polystyrene, or nylon matrices with various types of reinforcement such as synthetic, cellulose or carbon fibers could be evaluated. In addition, the experiments could be extended to study the effects of the hydroforming process on the forming of thermoset materials.

6.2. Future Numerical Work

Even though the preliminary results of the modeling already completed demonstrate that there is correlation between the trends predicted by the model and the actual experimental results, a more detailed numerical analysis needs to be accomplished to accurately model the hydroforming operation.

As illustrated in the numerical analysis section, the current work hardening model being used in the analysis shows the same trends but the accuracy of the strain values can be questioned. The preliminary work hardening was based on a power law equation derived from the uniaxial stress-strain data provided by Azdel. As shown by Koziey et al [30] the use of uniaxial data to predict the behavior of biaxial deformations is very difficult and leads to discrepancies between the model and the experimental results. Therefore the model needs to be refined to more accurately represent the deformation behavior of the composite material.

One way to refine the model would be to compare the force-displacement data of the experiment with the force-displacement data from the model. From this information a theoretical stress-strain curve for the biaxial stretching of the material could be determined and used as the work hardening curve in the model. This should allow for the more accurate representation of the hemispherical shaping process as it is being performed experimentally.

Once the work hardening curve has been adjusted to better represent the actual experimental procedure, adding a supporting fluid pressure on the punch side of the material will be needed in order to correlate the modeling with the changes being to the experimental procedure. This would eliminate the material sag that has been identified and would allow the numerical model to reflect the changes being made to the experimental set-up. The inherent complication with this aspect of the modeling is determining whether the commercial code MARC has this capability. It is desired to create a pressure load on the punch side that will be removed once the punch comes in contact with the material (i.e. no additive punch and pressure loads acting at the same material point).

The next change that needs to be made to the commercial code modeling is an evaluation of the effects that changes in temperature may have on the overall process. Based on the nature of the thermoplastic composite material, an increase in temperature should have a profound effect on the stress levels within the material. The current model utilizes an isothermal assumption that may not be entirely accurate. Therefore, in order to optimize this part of the process the temperature effects need to be incorporated into the model to create an accurate prediction method.

Once these changes have been made to the model, and the results validated through the experimental work, the next modeling step that needs to be accomplished is a FEA modeling analysis that takes into account the anisotropic properties typically associated with glass fiber reinforced polypropylene thermoplastic material. This will require some additional material tests to determine its behavior in different directions. Once that data is collected a phenomenological yield function can be developed and incorporated into the finite element model to represent the through-thickness and planar anisotropy of the composite sheet during the hydroforming process.

If good correlation is found between this FEA analysis and the experimental results, then there should be no need for the development of a specialized finite element code for the hydroforming manufacturing process. The natural progression, once this point has been reached, is to change the shape of the model from the hemispherical punch to the elliptical punch, and eventually to the tapered square, validating the results through experimentation.

If the correlation between the experimental and numerical results for the three punch configurations is not adequate then the development of a specialized finite element code for the hydroforming of composite materials process is warranted. To accurately model the forming process of composite materials, it is imperative to study the macroscopic and microscopic behavior of the material. Since composite microstructures are very complex, the homogenization method, as defined by Hsiao and Kikuchi [4], for composite materials, is a possibility for this analysis. Homogenization, in the broad sense, is replacing a complicated model with a simpler, equivalent model. The use of the homogenization method makes it possible to predict both the overall and local properties of processes in composites. This is accomplished in two steps. The first is to solve the appropriate local problem on the unit cell (microscopic level) and then to use this solution in the solution of a boundary value problem for a homogenized material.

There are two distinct advantages to the use of the homogenization method. First, the analysis of the unit cells at the microscopic level can be used to determine the material properties and the macroscopic constitutive equations. Secondly, the homogenization method allows for a localization procedure to be used in the evaluation of the microscopic field of deformation mechanics.

Current numerical analyses of the composite processing technologies all tend to have the same basic principles. There has not been a significant amount of research conducted on the micromechanical behavior of thermoplastic material as the material temperature fluctuates during the forming process. By adapting the homogenization method [4], and applying it to the hydroforming process, a numerical analysis could be developed that accounts for the thermal differences of the part during the shaping process, as well as the changes and interactions of the microstructure of the composite material.

Chapter 7

CONCLUSIONS

Fiber-reinforced composite materials are gaining popularity as substitutions for many of the weight critical components in the aerospace and automotive industries. Currently there exists a need for forming and shaping methods that can produce complex structures utilizing random fiber, continuous-fiber or woven-fiber composites with limited wrinkling and distortion. One manufacturing process that could achieve this desired result is the stamp hydroforming process.

The process of hydroforming, unlike conventional stamping, involves supporting the bottom of the sheet with a bed of viscous fluid during the stamping process. This external support provides a through-thickness compressive stress that will improve the formability of the sheet by delaying the tensile instability (i.e. necking). Also, this external support reduces the formation of wrinkles due to tensile frictional forces.

Through a series of preliminary experiments using a specially designed die set a complication associated with material sag arose. Through the use of a thin vinyl diaphragm material the benefit of a hydrostatic pressure for the processing of thermoplastic materials was demonstrated. A new die has been designed that should eliminate the material sag issue and allow for the application of a localized fluid pressure as the material is being formed.

A numerical analysis for the hydroforming process was conducted using the commercial code MARC. The numerical results correlated very well with the experimental results and exhibited the same material sag complications. Further modeling will be conducted in order to add an equalizing fluid pressure on the punch side of the material thereby simulating the new die design.

Further experimentation and modeling will need to be conducted in order to optimize the process with regard to the rupturing instabilities. The next step will be the evaluation of pure wrinkling instabilities and then the evaluation of a combination of wrinkling and rupturing instabilities. The end goal is to optimize the process with regard to both wrinkling and rupturing and to determine the optimum fluid pressure-punch stroke path that will lead to the production of high quality parts. Overall the experimental results, coupled with the numerical modeling, showed that the stamp hydroforming process is a viable processing method for thermoplastic materials that warrants additional attention based on the significant advantages in cost savings and part production accuracy.

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