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Analyzing the Formability of Reinforced Glass Fiber Metal Laminates in Isothermal Conditions

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Conflicts of Interest
There are no conflicts to declare.

ABSTRACT

Fiber metal laminates are sandwich materials comprised of altering layers of fiber reinforced composites and metal alloys. These materials can offer superior properties compared to the monolithic constituents such as superior specific strength compared to metals and better impact and fatigue resistance than composite materials. This paper investigates the stamp formability of fiber metal laminates using distinct material based on a reinforced glass fiber metal laminates. Specimens of varying geometry were stretched over a hemispherical punch to elicit different deformation modes in the fiber metal laminates and a non-contact optical measurement system was used to measure the surface strain during deformation. These experiments analyzed the effect of the deformation mode on the formability of the laminates. The results from the experimentation were used to assess the deformation behavior of the fiber- metal laminates and to identify the safe forming limits of the materials.

Keywords: ICT, KNOWLEDGE SOCIETY, LITERATURE REVIEW, MOBILE LEARNING, MULTIMEDIA MOBILE DEVICES

1. Aim of the research

The aim of the paper is to provide a fundamental understanding of the formability of the fiber metal laminate

1. Assessing and analyzing the forming behavior of reinforced glass fiber metal laminates.
2. Determining the effect of temperature on the formability of reinforced glass fiber metal laminates.

2. Introduction

Evidence of human-driven climate change is motivating research into advanced materials. Such materials are primarily of interest to the transport industry which is attempting to reduce the fuel consumption of aircraft and vehicles through the reduction of weight. Reduced vehicle weight is seen as a precursor for further efficiency improvements through the principle of 'mass decompounding'. Lower vehicle mass allows the use of smaller, more efficient engines or alternative power sources such as hybrids or fuel cell technologies.

It has been estimated that the reduction in mass using composite materials is 20-35% and 40-65% using reinforced glass fiber and carbon-fiber reinforced composite materials respectively. The advent of low cost thermoplastic composites has led to studies of how existing low cost rapid manufacturing techniques, unavailable to thermoset composites, can be applied to them. The use of composite materials in the aircraft, allows these aircraft to transport larger quantities of passengers and cargo for lower fuel costs. This is significant when the highest cost to airlines is fuel.

The development of laminated structures can be traced to Germany after the Second World War. The bonding of metal layers was introduced due to the lack of heavy machinery to create built-up metal structures. It was found later that, due to this lamination, the laminated parts exhibited good fatigue properties. The first generation of FML systems utilized an aramid fiber reinforced thermoset composite called ARALL. This FML system was developed in the 1970s by TU Delft and Fokker. Studies of this material on F-27 wing panels showed great promise. A weight reduction of 25% was achieved while maintaining strength, and loads which would cause failure in monolithic aluminum caused only minor damage in the FML [4]. However, it was found that the blunt notch strength of the ARALL FAIL was critical, and premature fatigue cracks appeared at doubles when layers were bonded together to increase strength. Other deficiencies were also found in the ARALL FML systems, such as poor bonding between the aramid fibers and matrix material, moisture absorption and failure of the fiber/matrix interface, and fiber failure under tension-compression fatigue loading [5]. These problems led to the development of FML systems such as GLARE, which contains a glass-fiber reinforced thermoset composite. Studies showed that the GLARE FAIL was not only less expensive than the ARALL FML but also resulted in greater weight reductions and had superior fatigue resistance.

Fiber metal laminate (FML) systems are a composite material consisting of alternating layers of fiber reinforced composite and metal. The bonding of metal layers was introduced due to the lack of heavy machinery to create built-up metal structures. It was found later that, due to this lamination, the laminated parts exhibited good fatigue properties. Reinforced glass fiber metal laminates offer the ability to form reconsolidated sheets of material with a manufacturing time comparable to metals, a facility which would allow composite materials to be used in automotive applications. These materials also have the advantage that they can be heated and reformed repeatedly.

The most common method for mass production of components is stamp forming. This process makes use of a die, blank-holder, and punch. The die and punch are designed according to the desired final shape and the blank-holder is used to control the amount of stretching and drawing of material into the die. The most common material system used in stamp forming is metal alloys. Stamp forming of materials such as steel is a well understood process. However, the application of stamp forming to FML sheet materials has not yet been investigated thoroughly; only recently have studies begun to investigate the formability of FML systems when stamp forming is used. These studies, which will be reviewed in the following chapter, have found that it is possible to form FML systems. One of the major conclusions from these studies is that heating of the FML prior to forming can improve formability.

Production of components using stamp forming often involves a costly and time-consuming die design and die tryout process. In recent times, this process has been streamlined by using predictive modelling techniques involving finite element analysis (FEA). FEA allows relatively rapid and inexpensive determination of material formability and reduces the number of trials needed. The validation of a finite element model against established forming experiments, and which covers all deformation modes, allows the modelling of a range of complex components.

The experimental work contributes to understanding the formability of fiber metal laminates, including the development of a comprehensive predictive finite element model for the forming of fiber-metal laminates.

3. Experimental procedures

Fiber-metal laminates are combinations of materials with different chemical compositions, strengths, and other properties. This part summarizes the properties of the constituent materials and describes the manufacturing process used to create FMLs from these constituents.

3.1 The Material parameters

Thermoplastic composites exhibit a wide range of mechanical properties depending on the reinforcement and the matrix. A glass fiber reinforced composite has a high stiffness and low strain to failure. Due to its high strength-to-weight ratio, good weldability, machinability, formability, and good corrosion resistance the metal chosen for the outer layer of the glass fiber metal laminate was aluminum.

3.2 Characterization

The characterization experiments to obtain the stress-strain behavior of the composite materials were carried out. The dimensions of the experimental tensile specimens are shown in Figure 1.1.

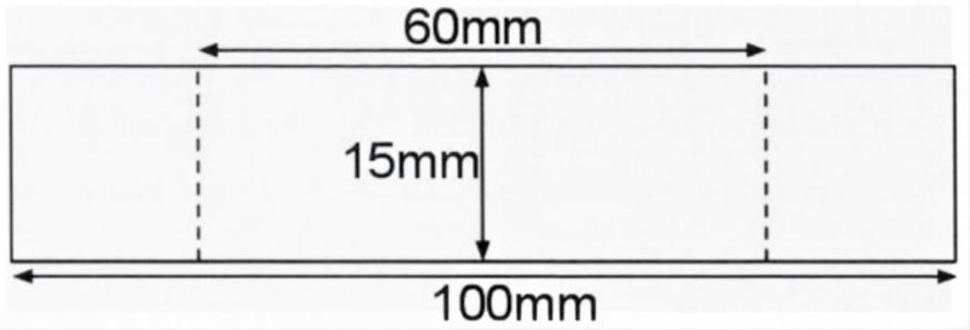


Figure 1.1: Characterization of sample

3.3 Stretch formation

The experiment dictate the parameters required to determine the forming limits of sheet metals such as the specimen and tool geometry, feed rate, lubrication, and data extraction methods. All experimental forming specimens had the fiber orientation aligned along the longitudinal direction of the specimens. This had the effect of reducing the amount of deformation available to the laminates due to failure at the fibers. The experiment procedure is described in Figure 1.2.

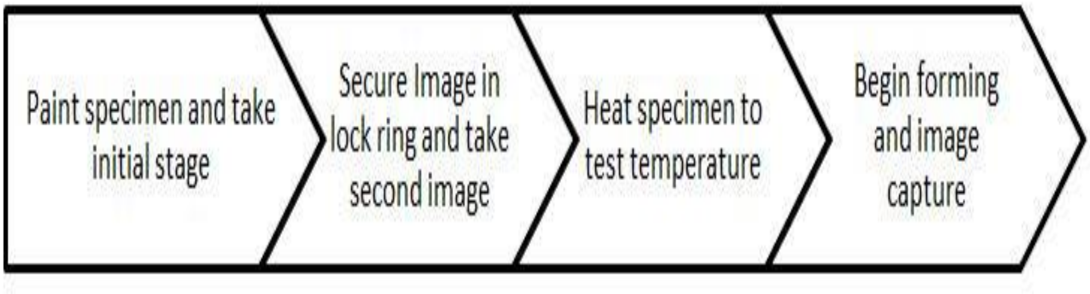


Figure 1.2: Experimental procedure

4. Thermal formability of FML

The forming behavior of a FML based on a reinforced glass fiber composite. The effect of specimen geometry and temperature on the strain behavior of the laminate during forming is investigated and the safe forming limits are determined.

The reinforced glass fiber composite specimens were subjected to a “pre-stretch" prior to forming. The effect of the “pre-stretch” in the reinforced glass fiber laminates was more severe due to the low extensibility of the glass fibers. The major strain in the laminates never exceeds 2%. The strain behavior of the specimens is also significantly different from the other specimens, with the strain behavior more closely aligned with plane strain, a trend which is visible in all results observed in the reinforced glass fiber specimens. The range of minor strain is also smaller, with more clustering around 0% minor strain at all major strain values.

The failure at the lock ring of the specimens is shown in Figure 1.3. It was found that only the reinforced glass fiber metal laminates specimens failed at the lock ring, with all other rectangular specimens showing significant strain increases or fracture in the center of the specimen. Premature failure at the lock ring limits the ability for the smaller rectangular specimens to provide accurate information about the forming limits in their respective deformation modes; however, due to failure occurring prior to any failure in the center of the specimen, it is expected that the failure limits generated by these specimens will be more conservative.

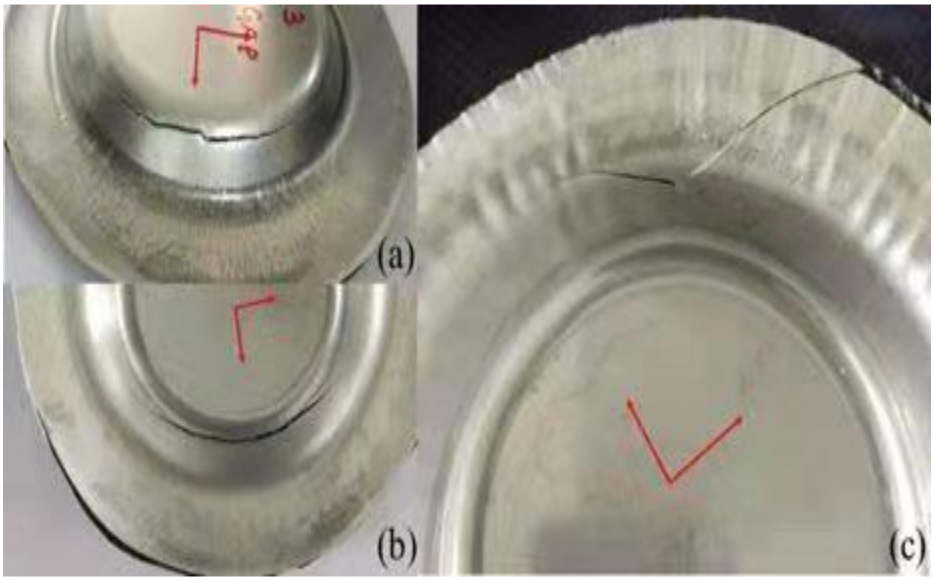


Figure 1.3: Failure at lock rings [2]

4.1 Pole region evolution

Figure 1.4 shows the evolution of surface strain at the pole of both the rectangular and hourglass experimental specimens. There are three distinct regions for the evolution of strain at the pole of the reinforced glass fiber metal laminates specimens: the pre-stretch, biaxial, and proportional loading regions. However, there are significant differences in the behavior of the material systems. The reinforced glass fiber metal laminates specimens fail at much lower major strain values due to low extensibility of glass fibers. This causes significant difficulty when determining whether the experimental specimens are inducing the expected deformation mode. It can be seen in the figure that a transition from biaxial stretch is occurring in the specimens; however, failure occurs before any meaningful results can be obtained for this deformation mode.

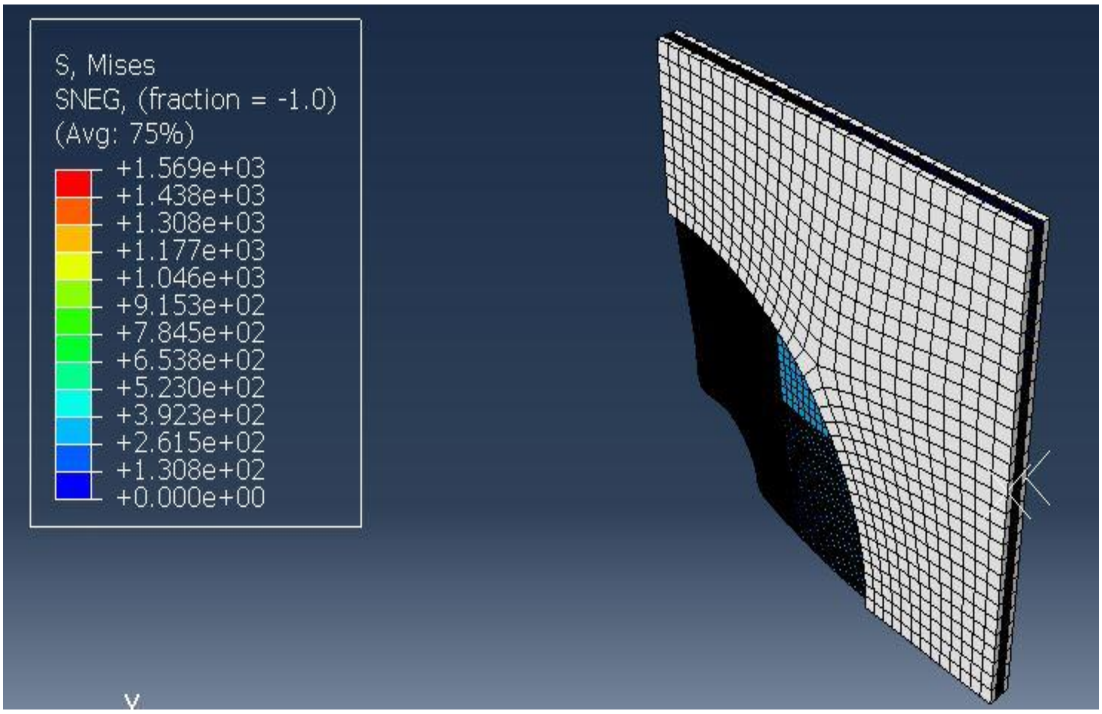


Figure 1.4: Strain in the pole region of tensile

The depth of the transition from biaxial stretch to the deformation behavior occurs at approximately 3-5mm. Figure 1.5 elucidates the nature of the change in deformation behavior at this depth which is caused by a change in the evolution of the minor strain. It can be seen that the evolution of the minor strain in the reinforced glass fiber metal laminates specimens does not exhibit the same trend as the other specimens. The minor strain for each specimen does not diverge as significantly as in the other specimens, with the wider specimens experiencing more positive minor strain and decreasing values as the specimen width decreases; instead, the reinforced glass fiber metal laminates specimens split according to specimen width and failure occurs before any divergence emerges.

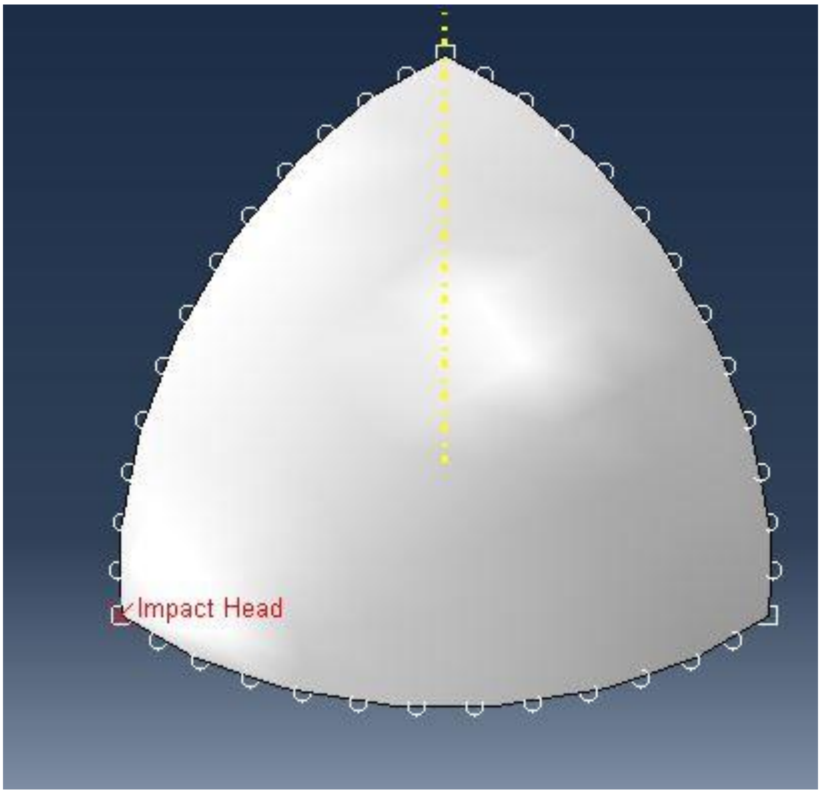


Figure 1.5: Evolution of impact head of the tensile

4.2 Failure region evolution

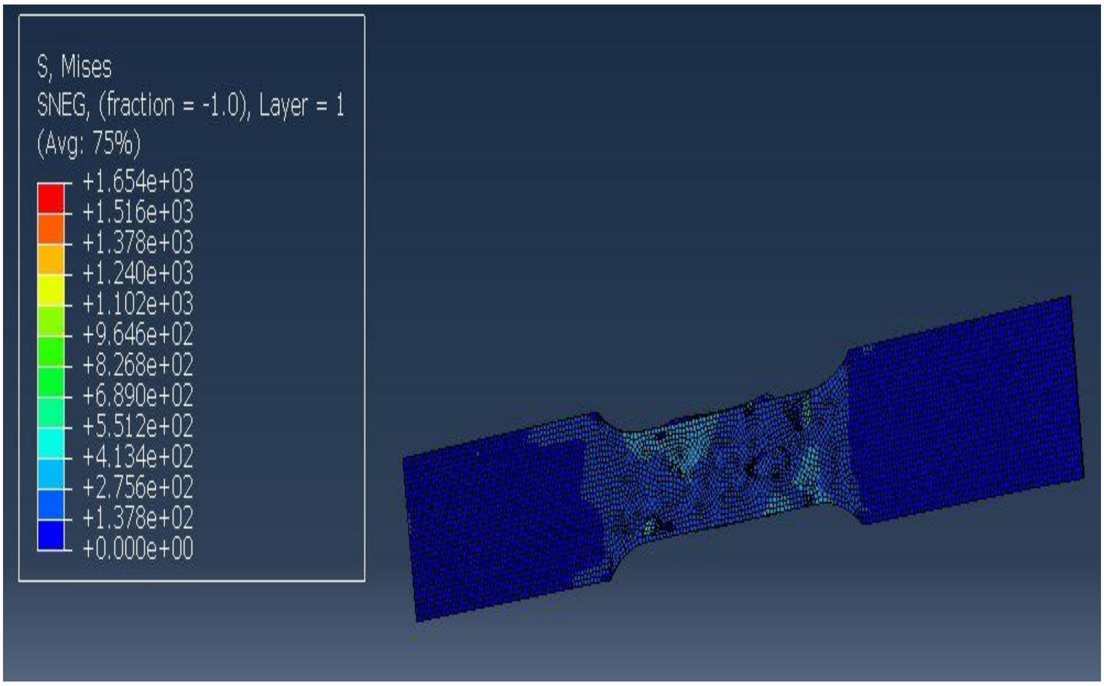
This depth is measured at the pole of each specimen and is therefore the distance travelled by the punch. It can also be seen that all specimens, other the 75mm rectangular specimens, failed before 21mm. This could be due to the 75mm rectangular specimen exhibiting delamination as its failure mode, shown in Figure 1.6. This delamination did not immediately cause a drop in punch force, which would have halted the process, or reduced the major strain on the surface, which would have signaled the onset of failure when processing the results. In all other specimens, failure is due to fiber breakage and subsequent tearing in the aluminum. The advantage of using specimens which have an hourglass geometry is that, compared to rectangular specimens, failure of the specimen can be induced in the region which is visible to the optical strain measurement system. Higher levels of friction at the pole prevent that region from deforming completely and therefore increase the amount of strain experienced by the regions surrounding the punch.

This region is where failure generally occurs. It can be seen that the failure region in all specimens that had visible failure shows a significant increase in major strain prior to the appearance of a tear in the surface aluminum.

Figure 1.7: Delamination in the specimen [4]

4.3 Behavior in surface strain

Figures 1.8 show the surface strain contours for the uniaxial tension, plane strain, and biaxial stretch specimens. These specimens show an interesting tessellated pattern compared to the other isothermal specimens. This behavior is caused by the twill weave, shown in Figure 1.9. In a twill weave, each weft floats across the warp yarns in a progression of inter lacings to the right or left, forming a distinct diagonal line known as a wale. Figure 1.9 shows the orientation of the wale, which corresponds to the non-highlighted section or the “raised” warp yarns, and the floating weft yarns where higher strains are seen. Higher strains occur in this region as the weft yarns are oriented in the lateral direction, which means that the load is being applied perpendicular to the glass fibers causing the lower stiffness matrix to deform. The lower stiffness provides greater extensibility. The other main result shown in these figures is the increase in strain on the surface of the specimen in the failure region. As stated in the previous section, failure of the reinforced glass fiber metal laminate layer initiates the failure of the laminate. It can be seen that the strain in the non-failed regions does not generally exceed 10%, which, when considering the bending strain, means that the sub-surface strain in the reinforced glass fiber metal laminate does not exceed 8%. Only the 25mm specimen does not show the increase in strain on the surface as failure occurred at the lock ring. It can be seen that the failure strain is much larger than the strain at other regions.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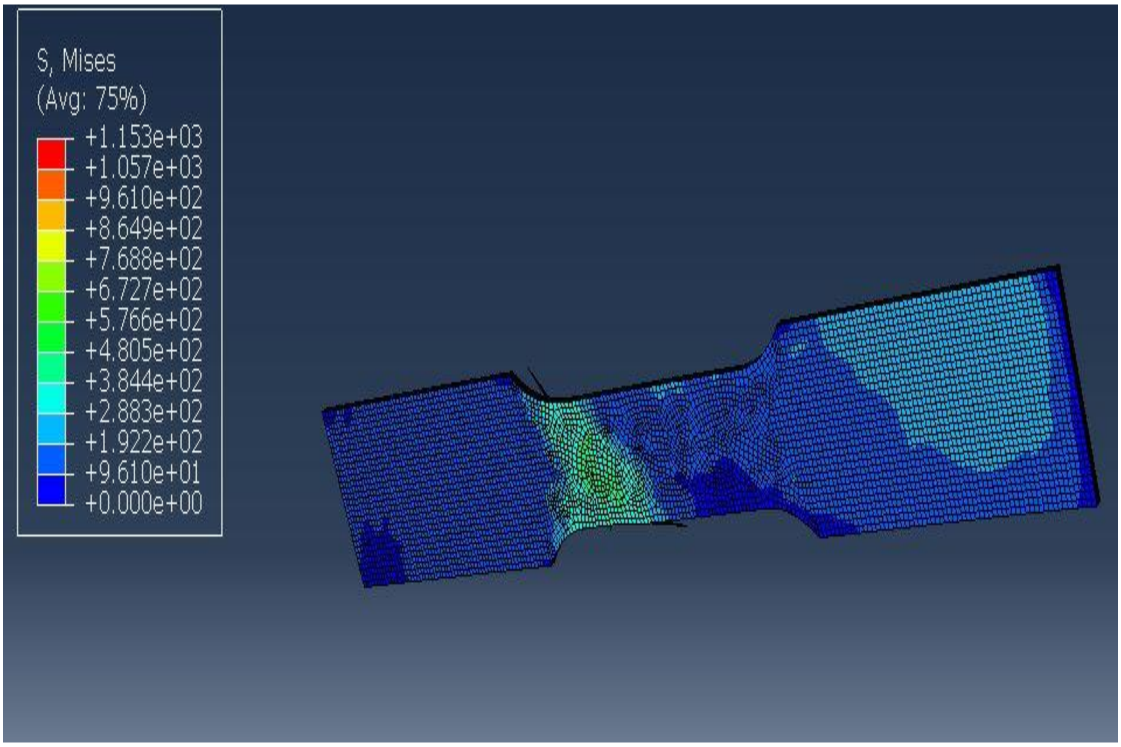
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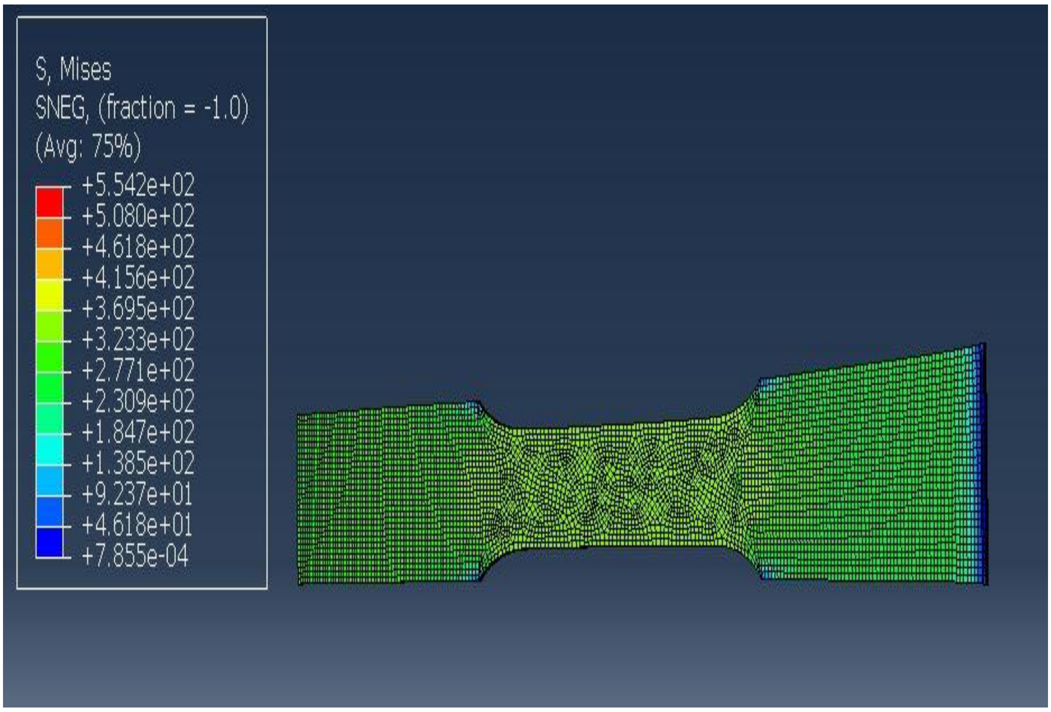

Figure 1.8: Strain contours for the specimens at different forming depths

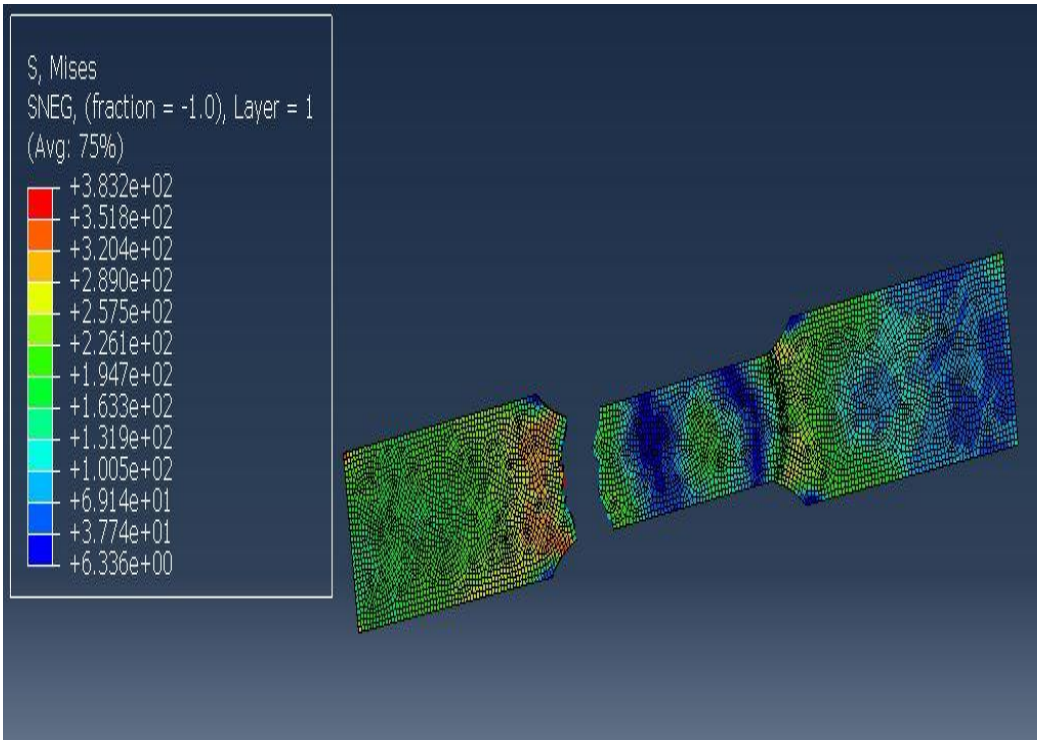

Figure 1.9: Breakage point of tensile at surface strain

Finally, the strain ratio at failure also highlights where failure is going to occur: due to the rapid increase in strain in the aluminum caused by the failure of the reinforced glass fiber metal laminate the strain ratio becomes much lower than the surrounding regions. The failure regions of the specimens are indicated by the red arrows in the figure.

4.4 The limit curve

The failure of the experimental specimens was dependent on the specimen geometry. The thinner rectangular specimens such as the 25mm and 50mm failed at the lock ring, the 75mm appeared to delaminate, and the larger specimens such as the 100, 125, 150, and 200rmn and all the hourglass specimens displayed failure which was visible to the optical measurement system.

The failure which occurred in the visible regions occurred to the side of the pole and along the longitudinal axis, and that failure occurred in the 200mm specimen in both the warp and weft fiber directions simultaneously. It has been discussed previously that the failure of the laminate is initiated by the failure of the reinforced glass fiber metal laminates layer. Supporting this assertion is that, contrary to previous studies on the forming of composite and fiber metal laminates systems, the reinforced glass fiber metal laminates exhibited some strain localization, where none existed previously, prior to the appearance of a tear. These figures show the rapid evolution of a neck in the aluminum layer leading to failure of the fiber metal laminates. This process occurs in 1 / 10th of a second, at 20fps, meaning that immediately after the fibers in the composite layer have failed the entire load is transferred to the aluminum layer which causes it to neck and subsequently tear.

Therefore, the forming for the reinforced glass fiber metal laminates specimen is much easier to determine than for either the aluminum or the other fiber metal laminates specimens. This is because the high strain in the failed region allows for ready determination of safe points marginal/necked points, and failed points. These FLCs agree with the theory that the glass fiber will fail at a strain of approximately 4-8%, with the marginal region occurring in the region between these strain values. The localized necking in the fiber metal laminates specimens can be seen from the failed points in the figure, which are at much higher strain values than can be sustained by a glass fiber composite.

In addition, they display significantly higher strain results than the marginal data points which were taken prior to an observation of a neck. The FLC for the fiber metal laminates shows that, at room temperature, the strain in the glass fiber limits the ability of the fiber metal laminates to deform using the stamp forming process.

5. Conclusion

This paper has assessed the formability of a glass-fiber reinforced fiber-metal laminate under isothermal conditions. The major and minor strain were measured at key locations (such as the pole and failure region and along the meridian line) and using a general overview of the behavior across the entire surface. These results were used to assess the forming behavior of the reinforced glass fiber metal laminates and subsequently develop a forming limit curve.

The failure of the reinforced glass fiber metal laminates highlights the effect that a composite with low strain to failure has on the forming of a fiber metal laminates. Unlike the other fiber metal laminates, there was a noticeable localization of major strain prior to the appearance of a tear in the fiber metal laminates. This can only be caused by failure of the reinforced glass fiber layer, which than transfers load to the aluminum, causing high strains and rapidly leading to tearing. This localization also occurs in the monolithic aluminum specimens; however, this is due to the formation of a localized neck in the aluminum which does not immediately proceed to failure. As expected, failure occurs in the fiber direction due to the lower extensibility of the fibers. However, failure did not always occur along the longitudinal meridian line. Due to the weave and unit cell of the reinforced glass fiber metal laminates layer, failure occurred in the fiber direction where the fiber was in the lower half of the composite; this did not always coincide with the meridian line. This was also highlighted in the surface strain contours, which showed the effect of the fiber, weave more clearly.

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