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NUMERICAL AND EXPERIMENTAL INVESTIGATIONS ON GFRP AND AA 6061 LAMINATE COMPOSITES FOR DEEP-DRAWING APPLICATIONS

NUMERIČNE IN EKSPERIMENTALNE RAZISKAVE GFRP IN AA 6061 LAMINATNIH KOMPOZITOV ZA UPORABO V POSTOPKIH GLOBOKEGA VLEČENJA

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Fibre-metal laminates (FMLs) are a multi-layered prominent class of hybrid composites gaining keen attention among researchers due to the combined advantages of the products used for aerospace and lightweight applications. This work involves one such investigation of hybrid sandwich laminate composites of aluminium sheets and a glass-fibre-reinforced thermoplastic (GFRP) core. FRPs can be conjoined with other lightweight materials to enhance the weight-to-strength forming performance and reduce manufacturing costs. However, the thickness reduction of the components for lightweight products makes the FRP-to-metal amalgamation a great challenge. The process of warm embossing is imposed to enhance the quality of single-lap adhesive bonding in FRPs and AA 6061 thin sheets. In this investigation, the formability of a FML made of AA 6061 and GFRP is predicted based on its deformation and wrinkle formation when it is processed during deep drawing. This research paper deals with analytical and experimental results regarding the prediction of deformation cause and effect in fabricated composite laminates with orientation angles of (90°; 0°; 60°; 30°; –45°; 45°). The method of evaluation combines the usage of ANSYS PrepPost with an explicit-dynamics module that bolsters designing, drafting and analysis.

Keywords: fibre-metal laminates, warm deep drawing, lightweight engineering, embossing process, adhesive bonding

Laminatni kompoziti s kovinsko osnovo in ojačitvijo iz vlaken (FMLs; angl.: Fibre-Metal Laminates) so pomembna večslojna vrsta hibridnih kompozitov, ki v novejšem času vzbujajo pozornost raziskovalcev in inženirjev zaradi svojih prednosti (odličnih mehanskih lastnosti na enoto mase) pri izdelavi izdelkov za letalsko industrijo. V članku je predstavljena eno od raziskav na področju sendvič hibridnih laminatnih kompozitov izdelanih iz Al pločevin in s steklenimi vlakni ojačanim termoplastičnim jedrom (GFRP; angl.: Glass Fibre Reinforced Thermo Plastic). Z vlakni ojačana plastika v kombinaciji z drugimi lahkimi materiali lahko ponudi enostavnejšo izdelavo lahkega kompozita in s tem cenejših izdelkov z odličnim razmerjem med mehanskimi lastnostmi (predvsem trdnostjo in trdoto) na enoto mase. Pri tem pa zmanjšanje debeline lahkih komponent izdelkov in istočasno spajanje plasti kovine in plastičnega jedra predstavlja velik izziv. Toplo spajanje so uporabili z medsebojnim lepljenjem tankih pločevin Al zlitine vrste AA 6061 in plasti s steklenimi vlakni ojačane plastike. V raziskavi so analizirali naravo oblikovanja izdelanih FML materialov, napovedali njihovo deformacijo in gubanje med postopkom toplega globokega vlečenja. Članek obravnava eksperimentalne in analitične vzroke za deformacije materialov in vpliv kota orientacije laminata (90°; 0°; 60°; 30°; –45°; 45°) na njegove lastnosti. Uporaba numeričnega orodja ANSYS PrepPost z natančnim dinamičnim modulom je omogočila zapleteno oceno izdelanih materialov, upoštevajoč pri tem njihovo načrtovanje, obliko in analizo.

Ključne besede: laminati vlakna-kovina, toplo globoko vlečenje, inženiring lahkih materialov, proces nastanka reliefa, adhezivna vezava (lepljenje)

1 INTRODUCTION

Lightweight engineering is an everlasting concept of evolution in aviation and also in automotive industries, especially as it plays a major role in the development of electric vehicles.[1,2] Efficient lightweight construction can be achieved using appropriate materials with their particular merits, each used for parts with locally varying mechanical requirements.[3,4] Metallic materials are already widely used in several applications and established in most production industries, especially in steel and aluminium.[5,6] The other type of material that is popular and most common in the market is fibre-reinforced plastic. Fibre-metal laminates (FMLs) are made up of metal (mainly aluminium) sheet layers bonded to composite-material layers that combine advantageous properties from both metals and composites.[7,8] These exhibit the following properties: resistances to impact and corrosion, reduced fatigue of metals, resistance to fire and low density.[9] The benefits of FMLs, particularly for aerospace applications, include the tolerance to damage and potential suitability for a lightweight modular design.[10] They are examined with respect to high strength and stiffness, considering fibre orientation as they are tough enough for a close interpretation.[11,12] Recent progress in the processing techniques for advanced composites allows us to

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apply these materials in complex-shaped parts for large-volume production.[7,13] Market requires their process ability, near-net shaping and overall cost efficiency in addition to mechanical performance.[10,12]

The FRPs work well with lightweight metals that can enhance the weight-to-strength structural performance and counteract the limitations of FRPs, reducing the overall fabrication costs.[14] The traditional production of FRP-metal hybrid composites includes mechanical fastening, welding and adhesive bonding, which are the three joining techniques.[15,16] In the case of mechanical fasteners like bolts and rivets, damage of continuous fibres occurs, causing stress concentration on the joints and resulting in a short lifetime of drills. On the contrary, adhesives are simple to use, weight-cost effective and capable of a smooth and uniform load transfer.[17] Adhesive fusing is also advantageous for ultra-lightweight hybrid structures due to the increased utility of thin sheets[18] so Huang et al. also examined the adhesive-embossing hybrid joining approach.[19]

Due to the improved usability of thin sheets, adhesive fusing is also helpful with ultra-lightweight hybrid structures[18] Huang et al. investigated a hybrid adhesive-embossing joining method.[19] The deep-drawn process allows us to produce high-strength lightweight parts more cost-effectively than with other methods and this method also allows us to produce complex parts. Deep drawing requires a blank, punch, die and blank holder with or without draw beads around the edge of the die. The punch pushes radially downward on the sheet metal, forcing it into the die cavity.[20]

Table 1: Laminate stacking sequence

Example	Laminate sequence
unidirectional	0°; 0°; 0°; 0°
cross-ply symmetric	0°; 90°; 0°; 90°
angle-ply symmetric	45°; –45°; –45°; 45°
angle-ply asymmetric	30°; –30°; 30°; –30°
quasi isentropic	0°; 45°; –45°; 90°
multidirectional	0°; 45°; 30°; –30°; 45°

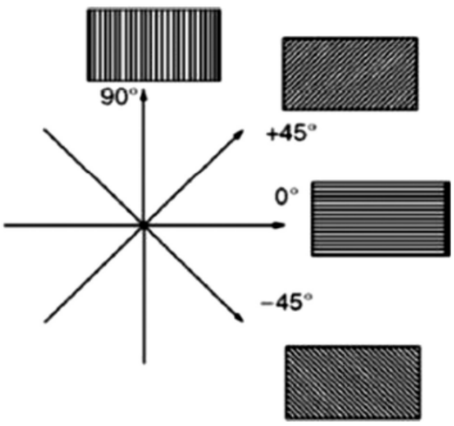

Figure 1: Angle of orientation

A laminate is made up of two or more unidirectional laminates or plies layered in various orientations. As illustrated in **Table 1**, the plies might be of various orientations and made up of different or the same materials.

For forming a metallic product, comparatively high forces are necessary. Meanwhile, few limited forces are disseminated by FRP as this may cause production failures. FRP can be sheared off at the boundaries to prevent the formation of wrinkles of the sheet metal in the soft FRP matrix. These adversities can be sorted out or depleted using suitable tools for temperature management. Fibre-reinforced plastics are strongly anisotropic; hence, the possibility of a unidirectional formation is a major threat. The stretching of layered fibres is not possible in the direction of the fibres. On the other hand, the inter-ply slip makes the production of FRPs perpendicular to the fibre direction quite simple.[21]

The basic benefits of laminates are the potentiality to curb and adapt the fibre orientation to the resisting loads. Plies add to the resistance of the laminate by aligning with the respect to the direction of the load. Fibres oriented at 45° can bolster the tension and uphold the compression at –45°.[22] This preliminary research deals with a laminate with one ply. If traditional forming techniques and manufacturing machines are already in use, the amalgamations of metal-FRP-metal sandwiches are the first choice for an easy change when working with FRP-metal laminates. In this research, only the metallic region is in contact with the forming tools. Since the FRP is placed in the metal zone, it is not sheared off in this forming process. Alternative proportionate progress between the sheet and tool is possible and so is conventional deep drawing.[23] Moreover, there is no adhesion betwixt the plastic and the die and the metallic sheets can also set up a defensive carapace (crust). This crust prevents the molten plastic from becoming displaced because of the necessary strong forces in the structure of the metallic segment. Accordingly, the subsequent forming of sandwich composites is investigated. The above discussion on FMLs carried out in the literature over the past two decades clarifies the research void in this particular area. Many researchers were keen on the FML analysis using diverse processing techniques other than deep drawing for making aircraft and fuselages. By identifying this unfathomed zone, the present research concentrated on investigating the unexplored processing method with the combination of aluminium-alloy series with fibre-reinforced polymers, specifically, AA 6061 and GFRP.

2 EXPERIMENTAL PART

2.1 Preparation of fibre-metal laminates (FMLs)

There are many divergent possibilities of amalgamating metals and FRPs, locally augmented to achieve FRP-metal components. This optimal fusion has different utilizations. In this process, the laminate, consisting of a metallic segment and fibre-reinforced plastic (FRP), is formed. In this way, the split manufacturing of individual components and consequent joining are evaded. In the initial stage, FMLs are prepared and consecutive joining takes place. For this experimental work, FML sheets were prepared using glass-fibre-reinforced polymer in composites and the high formability of aluminium in metals. The mechanical properties of aluminium (AA 6061) and GFRP are given in the **Table 2**. When comparing the mechanical properties of aluminium alloys, AA 6061 exhibits a greater formability than the AA 6019 sheet metal.[24] Fusion can be achieved in various ways. Before pasting the layers together, all the contact region of the sheets is sanded and cleaned with acetone and then air dried to remove impurities such as oxides and grease to enhance the binding performance of the laminate.[7,8] After this process, glass fibres are arranged according to the laminate sequence. Epoxy adhesive is applied to the cleaned upper side of the AA 6061 sheet metal. Arranged glass fibres are pasted in a sequence on the epoxy adhesive. In this case, the sheets and fibres are placed into the die together and bonded during the forming process. The metallic adherent is a 0.5-mm AA6061 sheet.[25,26] The used elastic epoxy adhesive is Konishi Bond MOS-8 with its working temperature ranging from –40 °C to 120 °C. It is a synthetic rubber adhesive exhibiting excellent bonding between glass fibres and metals. The adhesive is applied to join the sheets and glass fibres to achieve advantages such as high flexibility, medium to high initial strength and high heat resistance.[27] There are three varieties of fibre orientation between the glass fibre and aluminium sheets that were utilized to analyse the formability behaviour of fibre-metal laminates (FMLs) and the matrix after adhesive-embossing hybrid joining. The bonded FRP-metal composite was allowed to cure for 10–15 min at room temperature. SUS304 plate spacers were used to control the thickness of the adhesive layer.[28] The adhesive layer was uniformly distributed between the sheets and glass-fibre layers. The final thickness of the fibre-metal laminate was 2 mm. In addition, deep drawing was performed in dry conditions.[29]

Table 2: Mechanical properties of materials

Properties	AA 6061	GFRP
Density (g/cm^3)	2.70	2.58
Young's modulus (GPa)	68.9	85
Tensile strength (MPa)	124–290	480–1600
Poisson's ratio	0.33	0.21

2.2 Deep-drawing process

The deep-drawing experimental work was carried out under warm conditions, providing the basic results for formed parts including the fibre-deformation behaviour and formability nature.[30] The scheme of the experimental set-up used for warm deep drawing is shown in **Figure 2.**

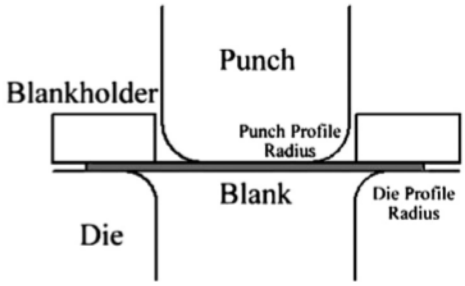

Figure 2: Different parts of the deep-drawing die set

The test rig consists of a draw-die flange with a circular shape, blank holder and punch. The dimensions of these components are listed in **Table 3**.

Table 3: Punch and die dimensions

Parameters	Values
Die diameter (mm)	50
Die-profile radius (mm)	5
Punch diameter (mm)	45
Punch-profile radius (mm)	20
Blank-holder diameter (mm)	50
Clearance between punch and die (mm)	2.5
Blank diameter (mm)	100
Blank thickness (mm)	2

The die and punch were made of MS steel with a set of forming tools and the blank holder was also made of MS steel.[31] The blank-holder pressure was controlled by applying a load with a servomotor. A PLC-operated 100-ton hydraulic press shown in **Figure 3** was used for deep drawing of laminated sheets of fibre and metal. The PLC controlled the movement of the blank holder and

Figure 3: PLC-operated 100-ton hydraulic press

punch using the limit switches. The punch speed of the press was 1 mm/sec. The punch diameter of 45 mm was used to study the effects of formability and deformation on the fibre-metal laminate.[32] A hemispherical punch has the advantage of applying a uniform load in all directions within the sheet plane. The fibre-metal laminate is deformed by a hemispherical punch and mould die under dry conditions, which are of primary importance for reproducing the real forming conditions.[33] In the current deep drawing of FML, the edges of the sheets were clamped with a blank holder. For this, a punch diameter of 45 mm and a drawing-die diameter of 50 mm were used. The target drawing depth was 20 mm. At the lowest process point, the forming process was stopped and the part was removed after solidification.[34] Deep drawing causes different stress states, thus resulting in elongation. The investigation of the formability of different materials can be performed using deep drawing of round cups.[35]

The forming load is transferred from the punch radius to the blank, through the drawn part wall to obtain deformation. The thinnest part defines the maximum stress that can be transferred to the deformation zone.[36] As described before, the angle-ply symmetric reinforced FRP shows a strong direction dependence on the formability. Round cups are rotationally symmetric, so the forming properties can be directly compared in all the directions within one part.

2.3 Finite-element modelling and analysis

Most of composite researches use finite-element analysis, and determination of the fibre orientation angle is one of the most important tasks of any composite study as the maximum critical buckling load is reached at the (0°; 90°) orientation angle.[37] This simplified model was created in ANSYS Workbench with the help of ANSYS Composite PrepPost and the deep-drawing simulation was conducted with ANSYS Explicit Dynamics.

The lower die, upper die and punch, all made of the MS steel material, were modelled as solid entities in the design software CATIA V5, creating a round cup with a diameter of 45 mm for deep drawing. In explicit dynamics, the blank-holder force was applied to the upper die and velocity was applied to the punch instead of the punch force. Initial designing and modelling of the fibre-metal laminate were conducted in ANSYS using Composite PrepPost. Aluminium alloy was selected to form the fibre-metal laminate, then glass fibre was arranged on the inner surface of the aluminium sheet metal. Glass fibres were arranged in the unidirectional orientation. Aluminium sheet metal was arranged after the glass-fibre ply to obtain a complete fibre-metal laminate. The adhesive was applied as a drop-off material between the sheet metals. Contact surfaces were defined as friction surfaces, thus no lubrication was required. So, the parameters influencing the formability of the fibre-metal laminate were found to include the blank-holder pressure, die radius and velocity of the punch.

The first layer was designed with a thickness of 0.5 mm and diameter of 100 mm, then the layer was defined as aluminium. The next layer was designed with the same dimensions as the aluminium layer, but defined as the fibre layer. The E-glass fibre was defined as a fabric in ACP PrepPost. The third layer was designed and defined as aluminium to complete the fibre-metal laminate. Therefore, the required fibre-metal-laminate thickness was obtained. To create bonding between the fibre and metal, a drop-off material was introduced. The drop-off material was also one of the important factors for the laminate strength and it also varied depending on the number of plies dropped off at a single station, the distance between subsequent drop-offs (the stagger distance) and the layup of a dropped sub-laminate. Epoxy resin was used as the drop-off material in this analysis.

As just the initial and final states of the blank shape were known from the experiments, numerical simulations were carried out to determine the behaviour of formability by means of the deep-drawing depth, at which contact occurred between the upper and lower sheets during the forming process.

3 RESULT AND DISCUSSION

3.1 Simulation and experiment result

The simulation was done with FMLs with different orientations of plies, including unidirectional, cross-ply and angle-ply orientations. There was a deformation of the cup with some wrinkles in the flange portion. In this numerical investigation, the formation of wrinkles and deformation capability of the FMLs with different orientations were analysed and compared with an experimental deep-drawn cup of FML. **Table 4** represents the deformation of a circular cup during the simulation and the experiment in deep drawing.

Table 4: Comparison of wrinkle formation in simulation and experimental deformation

Type of orientation	Blank thickness (mm)	Punch diameter (mm)	Die diameter (mm)	Radius of die fillet (mm)	Drawing speed (mm/s)	Initial blank diameter (mm)	Analytical simulation deformation (mm)	Experimental deformation (mm)
Unidirectional	2	45	50	5	1	100	20	17
Cross ply	2	45	50	5	1	100	16	12
Angle ply	2	45	50	5	1	100	16	13

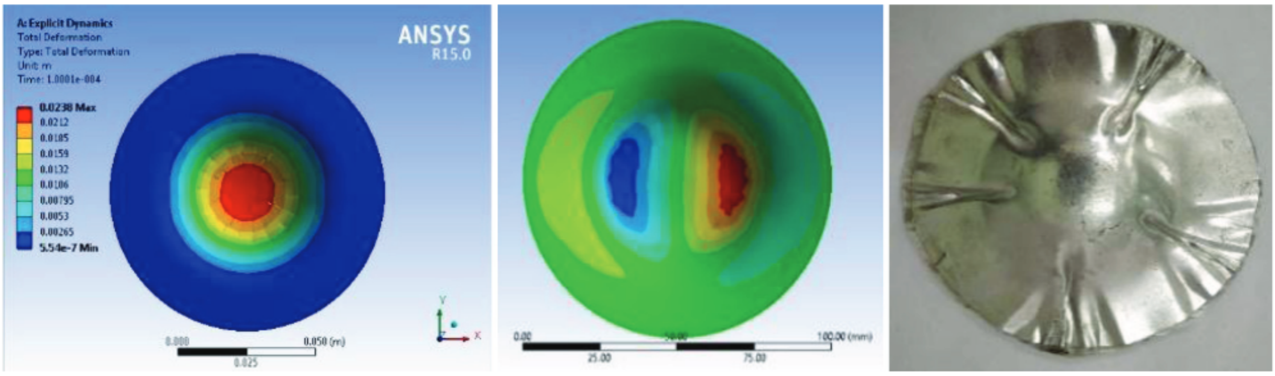

Figure 4: Analytical and experimental deformation of unidirectional FML

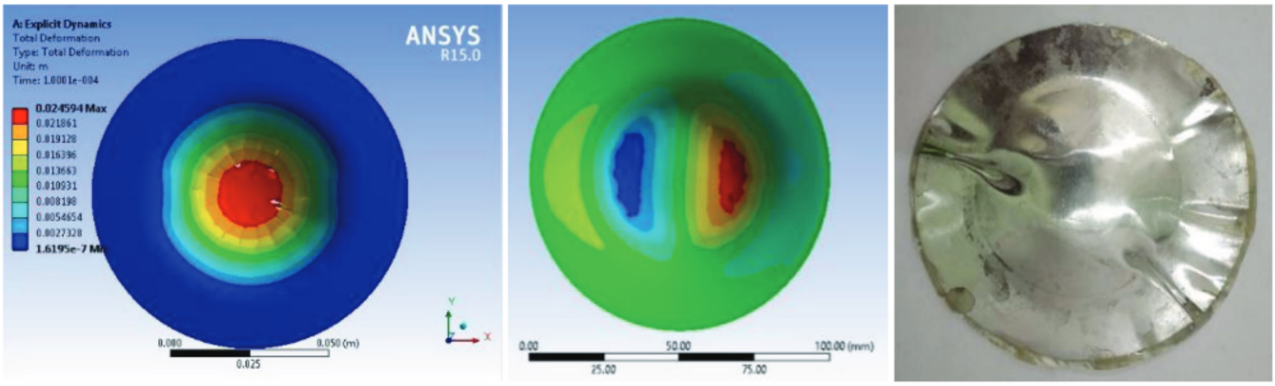

Figure 5: Analytical and experimental deformation of cross-ply FML

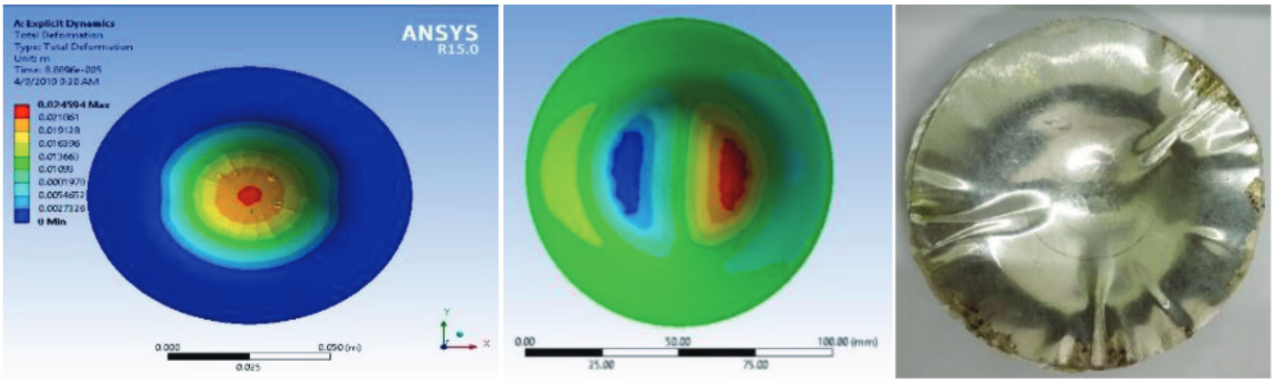

Figure 6: Analytical and experimental deformation of angle-ply FML

Figure 4 presents a numerical simulation of the total deformation and directional deformation, and an experimental image of the FML circular cup, composed of a unidirectional fibre ply, processed with deep drawing. According to the results obtained from the simulation, wrinkles start at 15 mm, leading to fracture at 20 mm, but according to the experimental result, wrinkles start at 11 mm and lead to fracture at 17 mm.

Figure 5 presents a numerical simulation of the total deformation and directional deformation, and an experimental image of the FML circular cup, composed of a cross-fibre ply, processed with deep drawing. According to the results obtained from the simulation, wrinkles start at 10 mm and lead to fracture at 16 mm, but according to the experimental result, wrinkles start at 7 mm and lead to fracture at 12 mm.

Figure 6 presents a numerical simulation of the total deformation and directional deformation, and an experimental image of the FML circular cup, composed of an angle-fibre ply, processed with deep drawing. According to the results obtained from the simulation, wrinkles start at 11 mm and lead to fracture at 16 mm, but according to the experimental result, wrinkles start at 8 mm and lead to fracture at 13 mm.

3.2 Wrinkle formation

Wrinkling of a sheet metal, usually in the part's wall or flange, is one of the most common flaws formed dur-

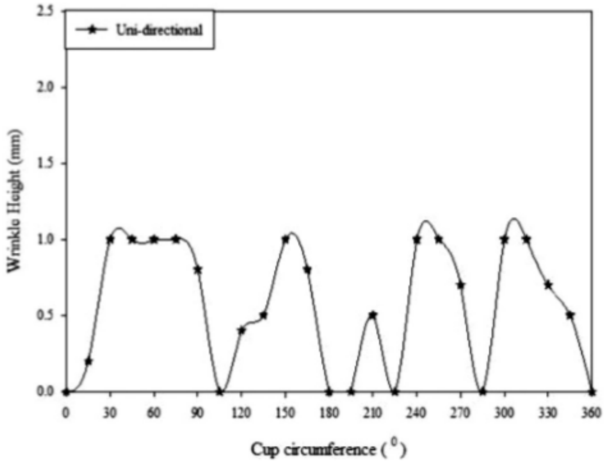

Figure 7: Distribution of wrinkles for unidirectional fibre-metal laminate

ing deep drawing. During this process, the blank's flange is subjected to the radial-drawing stress and tangential-compression stress, which can cause wrinkles. In the deep-drawing experiment, more specimens with different ply orientations were processed and the height of wrinkles was measured based on the cup circumference. Distribution of wrinkles was measured and a graph presenting the wrinkle height versus circumference of the cup for the unidirectional fibre-metal laminate specimen is shown in **Figure 7**. The unidirectional fibre-metal laminate specimen has more deformations than the other two specimens. In this case, more wrinkles were generated than for the cross-ply and angle-ply orientations; in addition, the height of wrinkles is relatively high for the unidirectional FML.

Figure 8 shows the distribution of wrinkles versus cup circumference and the wrinkle height for the cross-ply FML specimen. The cross-ply fibre-metal laminate specimen exhibits fewer deformations relative to the angle-ply orientation. The wrinkle formations are much fewer than in the case of the unidirectional ply orientation and the height of wrinkles is also relatively low.

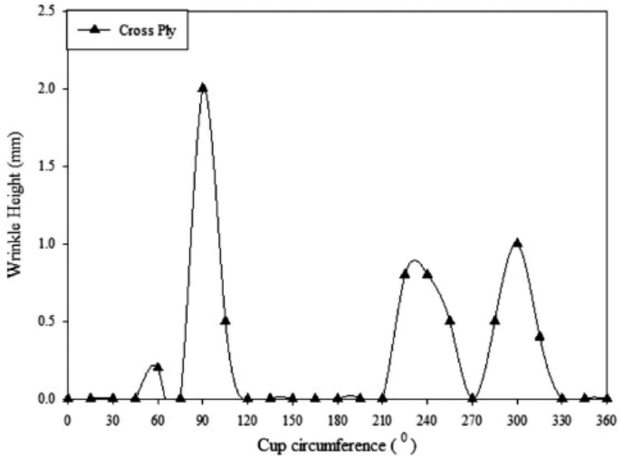

Figure 8: Distribution of wrinkles for cross-ply fibre-metal laminate

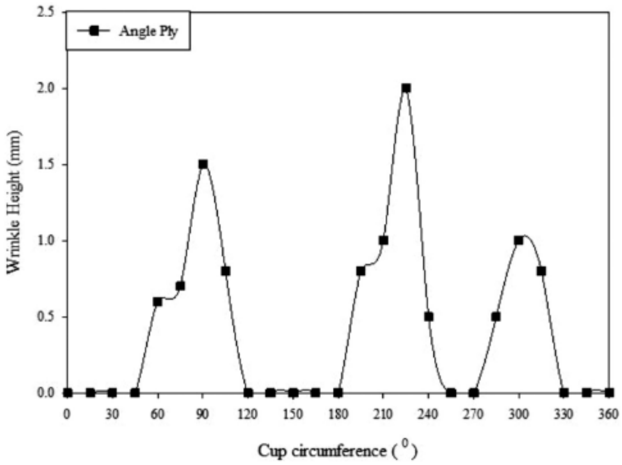

Figure 9: Distribution of wrinkles for angle-ply fibre-metal laminate

Figure 9 shows the distribution of wrinkles versus cup circumference and the wrinkle height for the angle-ply FML specimen. The angle-ply fibre-metal laminate specimen exhibits fewer deformations than the unidirectional FML specimen. There is no major difference in the deformation relative to the cross-ply orientation. The wrinkle formations are much fewer than for the unidirectional ply orientation and the height of wrinkles is also relatively low.

4 CONCLUSIONS

This preliminary analysis of deep drawing of FMLs including AA 6061 and GFRP with the help of the warm-embossing adhesive technique gave the following conclusions:

The drawing depth of the cup is highly proportionate with the orientation direction of stacking plies and holding pressure. The wrinkle heights become shallow and the pitch of wrinkles is smaller in the case of a blank-holder pressure enhancement. Due to the punch stroke, the sheet is stretched and the wrinkles disappear depending on their height.

Heating FMLs enhances the formability due to the metal's ductility as an alternative adhesive between the components increases the bonding strength.

When using a viscous adhesive interlayer to make sandwich sheets, zones that are not influenced by the geometry of the tools are formed.

The fracture initiation and the forming limit were successfully predicted using the analytical method and compared with the experimental verification. In addition, the results showed that the load on the blank centre strongly affects the formability and punch force. The punch speed and blank-holder force have remarkable effects on the formability of FMLs.

The result shows that deep drawing of FMLs is possible, but within limits.

The future scope of this research will focus on the limits in terms of attainable drawing depths, which are often determined based on cover-sheet cracking and wrinkling as well as composite-material fibre failure. The predicted simulation and analytical approach show much higher values than the experimental results, which will be investigated in more detail in the mere future.

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