FORMABILITY CHARACTERISTICS OF A SELF-REINFORCED POLYMER-METAL LAMINATE IN CHANNEL FORMING

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ABSTRACT

The inter-face bonding method and formability of a metal-polymer laminate system has been investigated for development of a novel material system for automotive panels. It was found that lap-shear strength and bond failure mechanism are dependent on the preparation method employed on the aluminium surface. Applying a sodium hydroxide surface treatment results in higher shear strength and a more cohesive bond failure than solvent cleaning. Investigations into laminates prepared with this method revealed that delamination was eliminated and springback was reduced with an increase in forming rate. A high forming rate also reduced the variation in stamp quality between different tool radii.

1. INTRODUCTION

Polymer-Metal Laminates (PMLs) have good sound and vibration damping characteristics. Steel based PMLs have been trialed in automotive panels for reducing cabin noise. Fibre-Metal Laminates (FMLs) are commonly used in low volume aerospace applications because of their excellent toughness, impact and fatigue properties. In the automotive industry, a need for reducing the vehicle weight while maintaining high specific mechanical properties has been recognised. In addition, improved noise and vibration damping characteristics are important considerations for passenger comfort and vehicle safety. PML and FML material systems present some trade offs for the above requirements. Automotive body panels made from these material systems need to be produced at a high production rate. Stamp forming provides an efficient manufacturing method for forming these material systems compared to the traditional methods. Bogaerts, Lossie and Vandepitte [1] found that there was an optimum drawing velocity for stamping of thermoplastic-based composites in terms of wrinkle minimisation. They also found that increasing processing temperature reduced the occurrence of wrinkles however it was accompanied by increased fibre slip. Conditions were determined to give satisfactory matrix viscosity and flow rates to optimise part quality. Friedrich and Hou [2] found that in stamping thermoplastic based composites panels into hemi-cylindrical forms, minimum pre-heat temperature and feed-rate were required in order to maintain stamping temperature in a region that would ensure high enough viscosity. Stamping below these minimum conditions resulted in inter and intra ply wrinkling.

Polymer-metal laminates used for sound damping purposes consist of alternating layers of metal and un-reinforced polymer. Kim and Thomson [3] found that high forming speed increased the transverse stiffness of the laminate and the degree of spring back and forming at elevated temperatures decreased the rigidity but improved the springback characteristics. Kim and Thomson [4] also studied the laminate separation behaviour of polymer-metal laminates using a combination of four-point bending and tensile tests. They showed that the mode of failure was dependent on the proximity of a free edge and that tensile failure of the adhesive occurred by a void growth mechanism. Investigations into the formability of steel based fibre-metal laminates by Mosse et al [5] revealed that it is necessary to pre-heat the FML to the melting temperature of the polymer matrix in order to achieve good formability. It was also found that although the constituent materials in the FML have significantly different load-unload characteristics a good quality channel could be produced by appropriate control of process variables. Further investigations by Mosse et al [6] into aluminium and glass/polypropylene based FMLs showed that heating the die and blankholder to 80°C minimised delamination and springback for a range of blankholder forces and tool radii however. Higher tool temperatures were found to produce delamination in channels stamped with small radii.

This study looks at the effect of aluminium surface treatment on inter-facial bonding using lap-shear testing and the formability of a laminate consisting of aluminium and a self-reinforced polypropylene based polymer layer (Curv, BP). Although Curv is 100% polypropylene, the reinforcement phase imparts some of the characteristics of a fibre-reinforced composite. The sensitivity of the laminate material to forming rate and tool geometries will be assessed by measuring the severity of delamination and springback in the channels.

2. EXPERIMENTAL METHODS

Materials and manufacturing

Laminates for lap shear testing were made using 1.6 mm thick 5005-H34 aluminium and a 60 μm thick polypropylene hot-melt adhesive (Gluco, Gluco Ltd UK). Two laminates were made by placing two layers of the adhesive between two sheets of the aluminium. The aluminium for the first laminate was cleaned using a simple solvent (acetone) wipe procedure. The aluminium for the second laminate was cleaned by immersion for 5 minutes in a 5% sodium hydroxide solution. The layers were stacked in a 200 x 200 mm picture frame mould and consolidated using a one-shot heating stamping process. The mould was heated to 160°C in a platen press then stamped at approximately 0.5 MPa while simultaneously being water-cooled. The polymer metal laminates (PMLs) were made with a 0.9 mm thick layer of a self-reinforcing polypropylene (Curv, BP) between two layers of 0.5 mm thick 5005-H34 aluminium. These layers were bonded with a single layer of the Gluco adhesive that was placed at each bi-material interface. Consolidation was completed using the heating-stamping procedure previously described and the final nominal laminate thickness was 2 mm. The prepared laminates were cut into 20mm wide strips using carbide tipped slitter disk on a milling machine and de-burred.

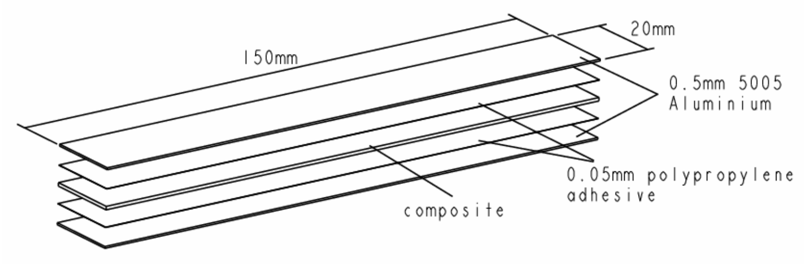


Fig. 1. Laminate construction

Mechanical testing

The effect of surface preparation on bonding between the aluminium and the PP adhesive was characterised using the double lap shear test, in accordance with ASTM D 3528-76. The nominal sample was width 25 mm and lap length 12.5 mm. Testing was conducted in displacement control at 1 mm/min on an Instron universal testing machine (model 4505). Scanning electron microscopy was used to elucidate failure modes on the fracture surfaces of the lap shear samples.

Stamp forming

The laminated strips were pre-heated to 160°C in the platen press before being transferred to a die set custom made for stamping channels forms at elevated temperatures. The die and blankholder were pre-heated to 80°C and the punch was at room temperature (25°C). This granted a temperature stamping window between 130°C and 150°C. A 50 mm offset was allowed between the punch tip and the strip before the blankholder was closed at a rate of 24 mm/second and a force of 3.5 kN. This was immediately followed by punching the channel to a depth of 41 mm at a pre-set feed-rate. Channels were held in the press for 60 seconds to allow them to reach steady state temperature conditions before being removed. A heat resistant polymer film placed on both sides of the laminate provided lubrication. Channels were stamped using 3, 5 and 7 mm die and punch radii and three punch feed-rates of 4.4, 28.5 and 53 mm/second. Three measures were used to assess the quality of the stamped laminate (Fig. 2): (i) the deviation in channel wall angle (Δ∅), referred to as springback, (ii) delamination area quantified by measurement side wall crack lengths with a vernier.

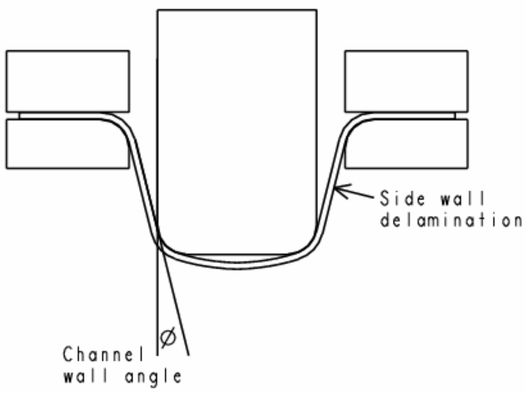
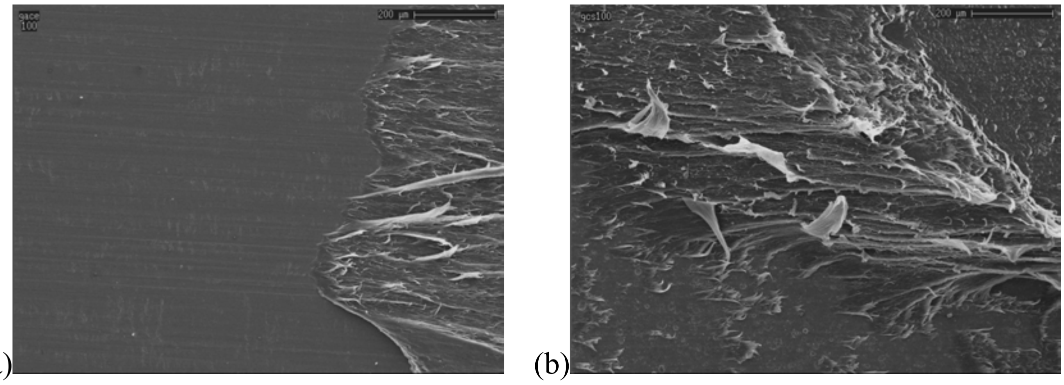


Fig. 2. Laminate channel quality measures

3. RESULTS

Lap shear strength

The average lap shear strength (with SD in parentheses) for solvent-cleaned and NaOH treated samples was 11.07 MPa (0.66) and 12.44 MPa (1.00) respectively. The micrograph in Fig. 3 shows extensive adhesive failure at the aluminium-polymer interface in the solvent-cleaned samples. On the other hand, there was extensive cohesive failure in the sample treated with NaOH as the aluminium is still coated with polymer. The NaOH treatment therefore improves bonding, most likely through greater mechanical interlocking, which results in greater cohesive failure and higher lap shear strength. Consequently, the samples for tensile testing and channel forming were prepared using aluminium that had been given the NaOH treatment.



(a) (b)

Fig. 3. Fracture surface micrographs of lap shear samples; (a) solvent wipe (b) sodium hydroxide treatment.

Forming

Springback is given as the deviation of the measured channel wall angle from the value determined for an idealised channel. The degree of springback in the laminates is given for a range of punch feed-rates and tool radii in Fig. 4. For all tool radii, springback was greatest for a low feed-rate and decreased rapidly as the feed-rate increased. At a low feed-rate the springback values for different tool radii differ significantly with smaller radii exhibiting greater springback levels. However, at higher feed-rates the results converge until they are within scatter of each other. The variation for a given radius also decreased with increased feed-rate.

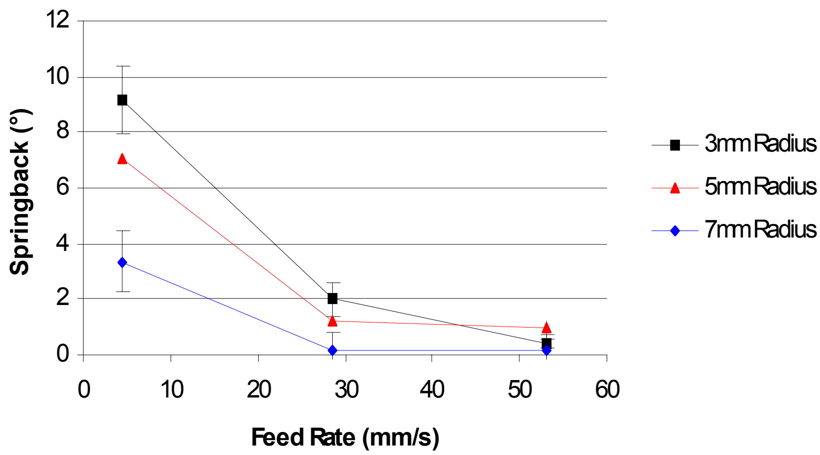


Fig. 4. Effect of tool radius and punch feed-rate on channel springback (error bars signify ± 1sd)

Fig. 5 shows a comparison of springback behaviour between the aluminium-Curv laminate formed at high punch feed-rate and results for plain 5005H34 aluminium obtained from a previous study [6]. Springback for the plain aluminium increased with tool radius, by comparison springback for the Curv-aluminium laminate remained almost unchanged.

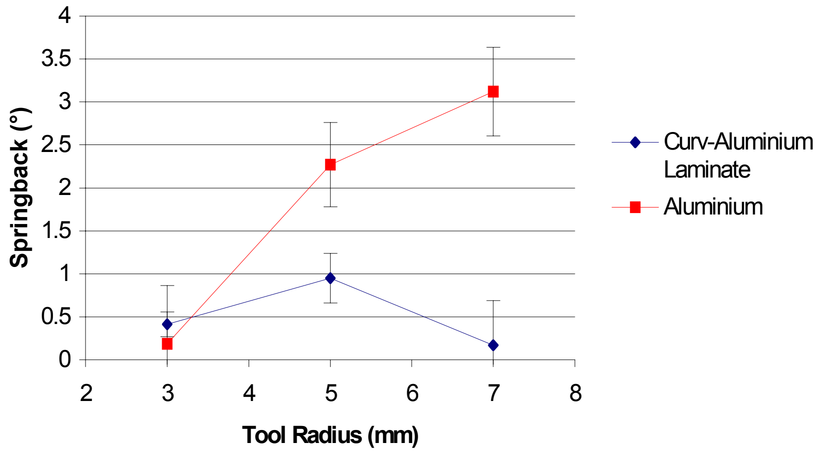


Fig. 5. Springback comparison between aluminium-Curv laminate stamped at 53mm/s and plain aluminium (error bars signify ± 1sd)

Estimations of the delamination area from the crack lengths in the sidewall region of the laminate channels are given in Fig. 6. An increase in feed-rate resulted in significantly reduced levels of delamination. This trend is supported by the micrographs in Fig. 7, which are from samples stamped with a 3 mm tool radius. Significant interfacial delamination is visible in the sample stamped at the 4.4 mm/s (7a), however delamination absent when stamped at 53 mm/s (7b). (The shear displacement noted in figure 7 is discussed in the following section). Another important point evident in Fig. 6 is that an increase in feed-rate reduces the difference between the delamination values for the three tool radii values.

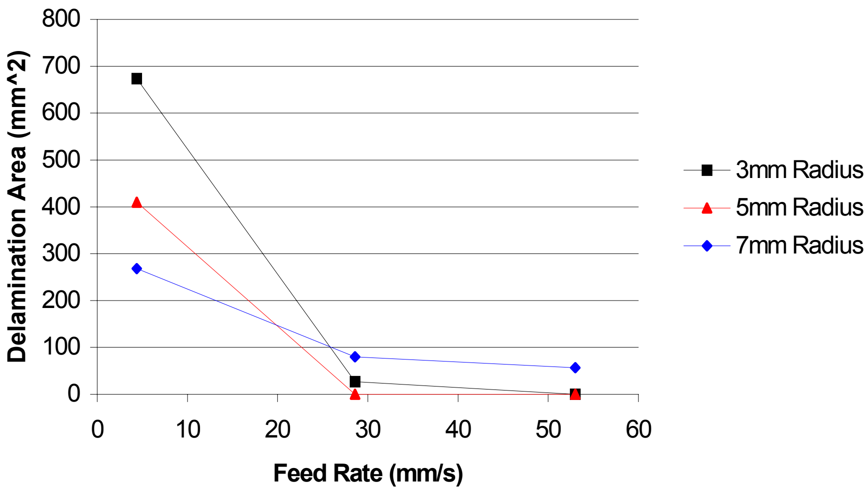


Fig. 6. Effect of punch feed-rate and tool radii on delamination area for stamped channels

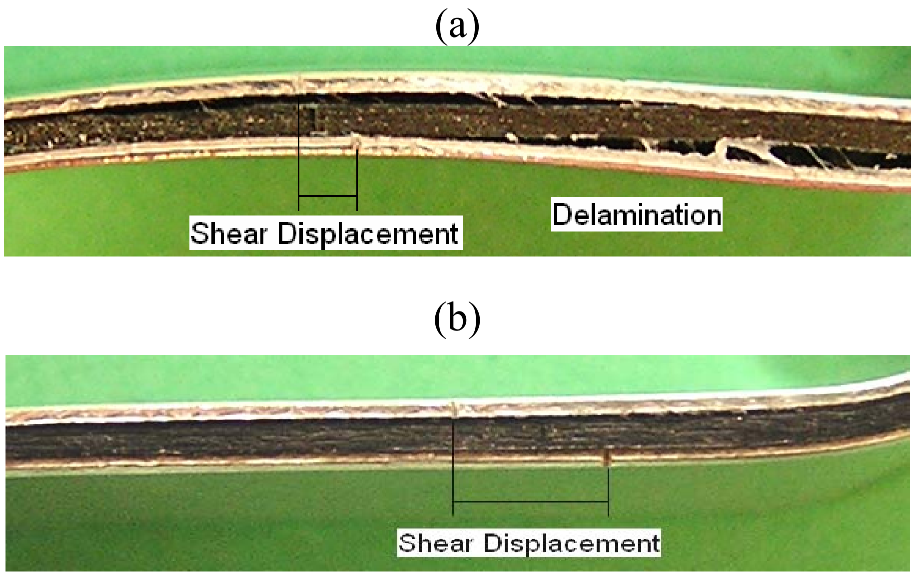


Fig. 7. Side-wall of laminate channels (a) low feed-rate and (b) high feed-rate. Score marks depict shear displacement of laminate layers**.**

4. DISCUSSION

The forming behaviour of the laminates may be explained by considering the behaviour of polypropylene, which exhibits increased viscous behaviour with an increase in temperature and strain rate [7]. Fig. 8 gives the temperature of the mid-region of the laminate and illustrates that laminates formed at a higher rate experience significantly higher temperatures for the duration of the stamp process than those formed at lower rates. In the case of the upper and lower feed-rate extremes investigated here, the difference is up to 30°C. This temperature processing window indicates therefore, that at higher feed-rates the polymer will melt, flow and re-form to the shape of the die more quickly than at the lower rates. The result of this process is that, unlike monolithic aluminium, the polymer layer in the laminate will not exhibit any of the elastic behaviour that causes springback; hence springback is lower.

The other point to consider is the effect of strain rate. It is likely that the forming process investigated here would impart flow rate sensitivity to the stress distribution through the laminate. This effect should manifest itself as a shear displacement, and this was assessed by measuring the change in length between gauge marks that were scribed onto the edge of selected samples prior to stamping. The sidewall images in Fig. 7 show an inter-facial shear displacement that is typical of laminates formed at low (7a) and high (7b) feed-rates. The displacement is clearly greater at the higher feed-rate, and is likely due to the greater flow of the polymer, as discussed in the previous paragraph. At low feed-rate, there is less shear displacement and also greater delamination. The quality of a formed laminate appears to have, therefore, a strong dependence on the ability of the layers to flow over each other; that is, the flow behaviour of the polymer is dominated by process conditions during the stamp process.

Overall, the results indicate that, for the given process conditions, a high punch feed-rate is necessary to minimise springback and delamination. It also improves the predictability of the stamping process by reducing the difference in springback between different tool radii and reducing the variation between repetitions of any individual radii. This suggests that sensitivity to geometry variations in a part can be reduced by increasing the forming rate. The delamination and springback values follow very similar trends with respect to punch feed-rate which implies that the integrity of the laminate is a necessary condition for restraining elastic stresses in the aluminium. Minimisation of damage resulting from the forming process will improve the mechanical performance of the part and the variation in part dimensions. In comparing the springback behaviour of 5005H34 aluminium and aluminium-Curv laminate (Fig. 5) it is apparent that the laminate is less sensitive to variations in tool radii and produces consistently less springback than the equivalent aluminium form. This is significant because it implies that springback would be more easily predicted in the die design stage.

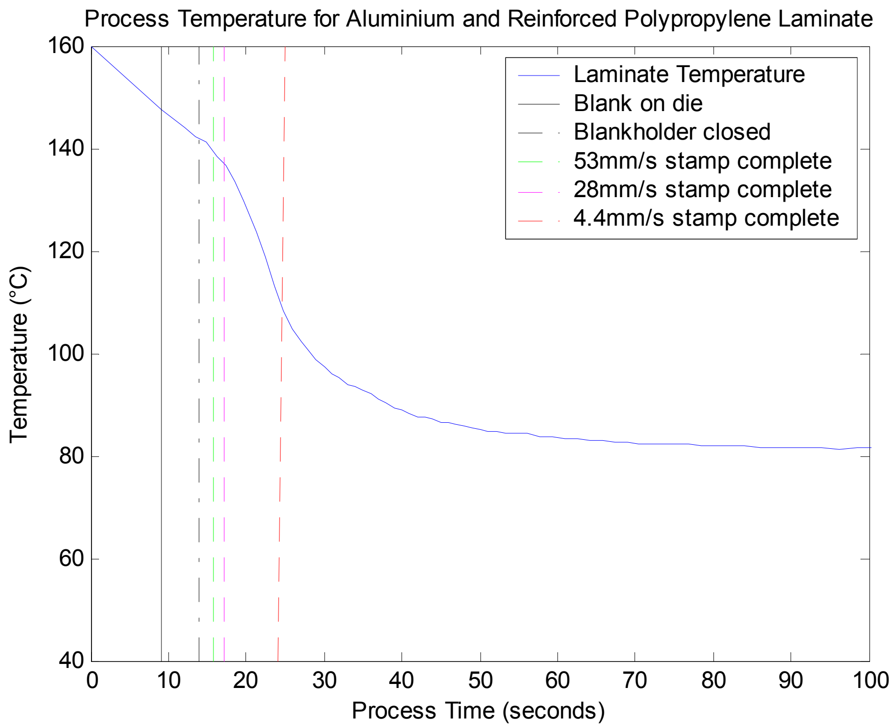


Fig. 8. Laminate temperature for stamp process

4. CONCLUSIONS

Sodium hydroxide etching is superior to solvent cleaning for bonding with a polypropylene based, hot-melt adhesive. Improvements in lap-shear strength and in the cohesiveness of the shear surface were achieved with this method. Stamp forming with a high feed-rate provides a method for maintaining the temperature of an aluminium-thermoplastic laminate without excessive pre-heating or press tool heating. A significant reduction in springback and the elimination of delamination was achieved along with a reduction in the difference in springback behaviour between different tool radii. In addition, the increased forming rate reduced the variation between identical experimental repetitions. Aluminium-Curv laminates stamped at a high feed-rate exhibited significantly less springback than plain aluminium stamped under similar conditions.

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