ADHESIVE BONDING OF SHEET FOR LAMINATED METAL TOOLING

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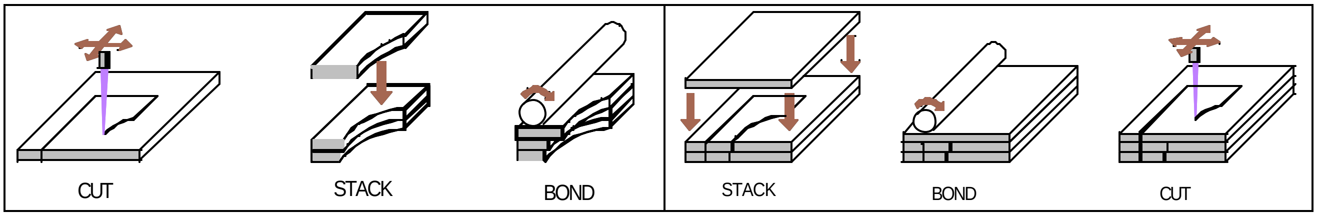
Abstract

There exists a significant body of work on metal laminate tooling built by the “cut-stack-bond” approach; however, automation with this method is difficult. Building laminations by "stack-bond-cut" sequence, on the other hand, is more amenable to automation. Two main challenges of "stack-bond-cut" sequence are blind contour cutting and bonding of the sheet. In this study, we investigate the hot-roller method of thermoplastic adhesive bonding for the metal laminations. Metal sheet, having thermal characteristics significantly different from paper, poses its own specific problems. During the bonding process, in order to achieve good bond strength, appropriate heat and pressure must be applied. As the stack builds up, thermal and mechanical properties change. This inconsistency of process conditions can potentially lead to part warpage, unless carefully controlled. Temperature measurements with a thermocouple embedded into lamination stack showed the effect of bonding process parameters on the laminate temperature.

Introduction

Using laminations (i.e., material in sheet form) for layered manufacturing (LM) avoids phase transformations with attendant shrinkage (as in powder sintering) and allows easy process scale-up. Adams et al. [1] produce working tools from steel laminations 1-3 mm thick, but have to resort to a finish milling step to achieve acceptable surface quality. Himmer et al. [2] propose to fabricate injection moulds by (1) joining flux-coated 2.5-mm-gauge aluminum through heat treatment near the flux melting temperature and (2) finish milling. Walczyk and Dolar [3] present results of tests on several epoxy and alumina-based adhesives used to bond aluminum laminations.

The “cut-stack-bond” approach (Figure 1a) adopted by above authors involves (1) cutting out the desired part’s profile at each lamination; (2) assembly (stacking) of the profiles, and (3) bonding (mechanically with fasteners, adhesively, or by welding). The primary drawback of this approach is the complexity of handling the cut-out profiles between the cutting and stacking steps, requiring indexing, transporting, and alignment. This complexity makes *automation* of the process highly impractical. An easier-to-automate alternative is a “stack-bond-cut” sequence (Figure 1b). This method has been applied in Laminated Object Manufacturing (LOM), but the sheet materials have been limited to paper, polymers, and ceramic composites [4]. Replacing soft materials with metals is a challenge, however, due to difficulties with “blind” cutting of metals (i.e., cutting only to the depth of the sheet’s gauge) [5]. This paper presents results of experimental investigation into thermal mechanism of adhesive bonding of metal laminations.



(a) (b)

Figure 1. Two possible sequences for producing laminated objects: (a) cut-stack-bond and (b) stack-bond-cut.

Bonding of Metal Laminates

There are several alternatives for metal sheet-to-sheet bonding. First, heat-activated polymeric adhesive (used in paper-based LOM process) can be also applied to metals. This kind of bonding is the easiest to implement in an automated process since the adhesive can be pre-applied to the sheet and subsequently quickly activated by heat and pressure. Other methods, such as welding, soldering and brazing may offer higher strength and high-temperature resistance, but they require expensive equipment and complicated processes. Therefore, polymeric adhesive bonding was selected for our initial trials.

In order to bond two solid sheets, a liquid adhesive should be spread and solidified between the two surfaces. The reason this results in a strong bond is that the liquid conforms to the surface shapes of the two solids being joined. This permits close contact between the surface of the liquid (adhesive) and the surface of the solids (adherends). Such close contact is necessary since the forces which act to hold the matter together are the same ones which to a large extent are responsible for the strength of the adhesive joints.

The process of adhesive application usually consists of spreading a thin layer of liquid adhesive between the surfaces to be attached and pressing these surfaces together. A joint is formed when the viscosity of the liquid layer is increased by such mechanisms as solvent permeation or evaporation, polymerization, and cooling until solidification. The requirement for optimum adhesion is good wetting of metal sheet by adhesive. In order to achieve good wetting, appropriate heat and pressure should be applied since heat lowers the viscosity of adhesive and pressure helps to spread the adhesive onto the surfaces. Insufficient heat/pressure may cause weak interlaminar bonds or even delamination. Excessive heat/pressure may cause the material degradation. Therefore, it is important to control accurately the heat and pressure in bonding process.

Besides bond strength, other factors, such as cure speed, cure method and suitability for use in automated production, will all play a role in determining the best adhesive for a specific application. First, because thin-gauge (0.1-0.5mm) aluminum or steel sheet will be used as the laminate, the adhesive layer must be kept to a minimum thickness. Second, high bond strength and good temperature resistance are important because of the intended functional tooling applications.

Two basic types of adhesives were considered: solvent-based and film. Solvent-based adhesives are spread evenly along the material to be bonded before the solvent or water is evaporated to create a bond. The adhesive can then be activated using heat and pressure. Film adhesives facilitate manual application since they result in uniform, controlled bond-line thickness. Film adhesives were used in the tests reported herein.

Literature Survey

A heated roller is used in paper-based LOM to apply the heat and pressure to the laminate. For our first prototype, we have adopted a similar system. There have not been to the authors' knowledge reports of thermal bonding investigations for thin metal laminates. Following is a brief overview of such work for the non-metallic laminates.

Park et al. [6] determine the optimum range for the heater temperature and speed settings using a commercial LOM machine by conducting tensile tests on bonded paper specimens. Chen [7] measures the heat transferred across the paper sheet by placing a thermocouple underneath it. Results are summarized in paper bonding curves. Each curve represents temperature rise in the adhesive as a function of roller speed at a fixed roller temperature. Curves show that the temperature rise decreases with increasing speed and decreasing roller temperature. It was also noted that the effect of roller pressure is not very pronounced.

Pak and Nisnevich [8] develop a mathematical model of the relationship between temperature at the arbitrary depth of the part and the LOM-process parameters such as temperature, speed of the heater, and pressure exerted by the heated roller. Flach et al. [9] also develop a mathematical model that describes the heat transfer during building of ceramic LOM parts. The thermal behavior of a part is determined by heat transfer to the part from the roller, heat conduction within the part itself, heat loss from the part to the metal base plate, and heat loss to the surroundings. The appropriate differential equation and boundary conditions were set up for a rectangular geometry part and then, together with appropriate initial conditions, material properties, and heat transfer coefficients, numerically solved to reveal the temperature distribution within the part. By tuning one of the model parameters (roller-to-part heat transfer coefficient), good agreement was obtained between predicted temperatures within a part and the actual temperature as measured by embedded thermocouples. In Flach et al. [10] the above model is used to investigate the effects of varying certain parameters during a number of simulated LOM builds. It is found that chamber air temperature and base-plate temperature combination are the most effective in controlling of the overall part temperature. The roller temperature proved to be the most effective in determining the temperature of the surface layers of the part.

Sonmez and Hahn [11] use Finite Element method to analyze the stress and heat transfer distribution in paper-based LOM. Stress analysis results provide the heat transfer model with an estimate of the contact area between the roller and the laminate. Effect of roller radius, laminate built-up thickness, and roller speed on the thermal time history is examined. They find that thickness of the built-up laminate impacts the stress distribution, larger diamter results in greater contact area, and that roller speed must be below certain value for successful bonding.

Bonding Temperature Measurement Experiments

Objectives: These experiments aimed to measure the temperature profile in the steel laminate while a heated roller is passing by at different rolling speeds, pressures and temperatures. This information would help in setting appropriate process parameters for metal laminate bonding.

Equipment: Figure 2 shows the heated roller used in the experiments to apply the pressure and heat in order to bond the metal laminations. The roller is carried by two supports which are mounted onto a belt-driven linear stage. One axis is driven by a stepper motor via Gemini GV motion controller while the other axis is mechanically linked to it by a drive shaft to assure synchronous movement. The pressure is controlled by adjustment of two springs which transfer the horizontal spring force to a vertical pressure via two L-shaped pivoting arms. By varying the spring compression from 0 to 40 mm, the roller downward force can be adjusted from 11 to 65 kg. A 650-Watt rod-shaped heating element located along the centre axis of the roller is PID controlled to within ±0.1°C using feedback provided by a built-in thermocouple sensor.

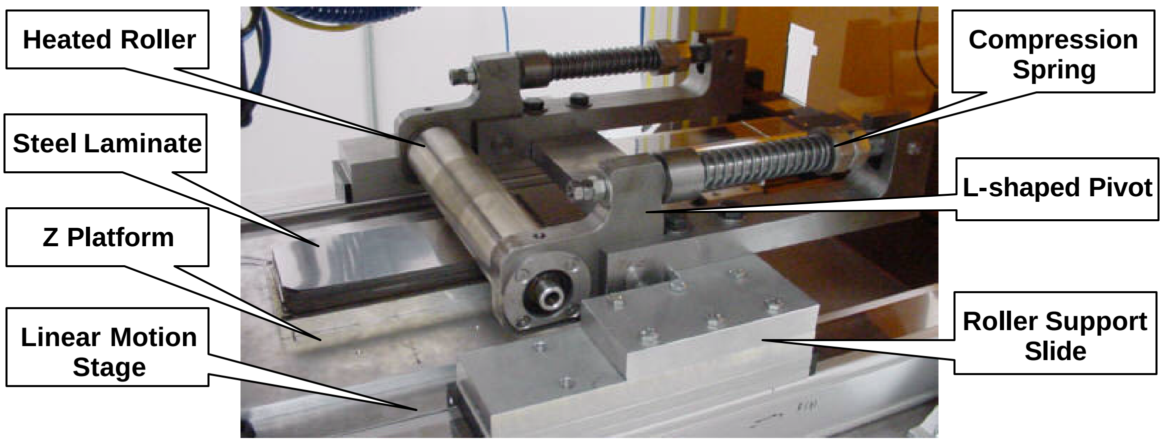
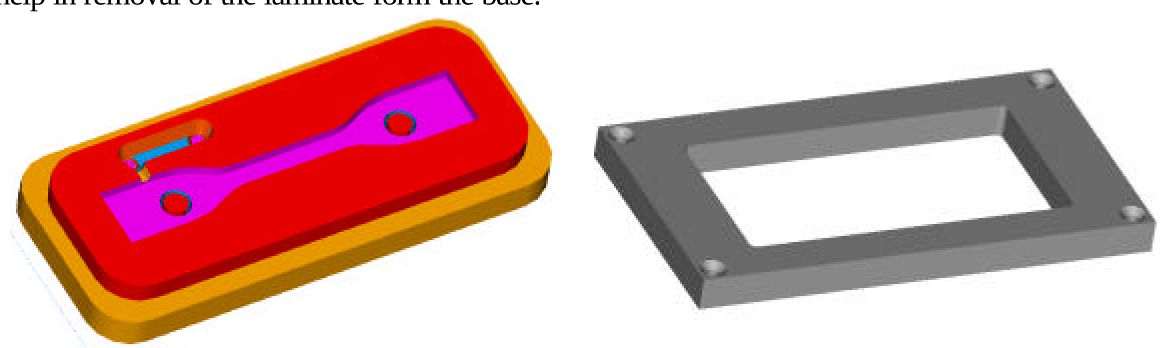


Figure 2. Heated roller and steel laminate.

Laminate Material: The laminate comprised 0.12-mm plain-steel shim stock and Scotch 467MP film adhesive from 3M. The 467MP is made from 200MP high-performance acrylic adhesive (50 microns) and polycoated Kraft paper liner. Temperature measurements were made during the building of a laminated injection mould insert (Figure 3a). A half-inch thick aluminum alloy block served as the base (Figure 3b). In the middle of the block, a square slot was cut through to assist in extraction of the laminate at the end of the build. The first layer of steel sheet was fixed to the block by gluing the four edges to four sides of the slot. The square block cut out from the original shape was then reinserted within the opening to provide support. When building was completed, the cut-out block was removed and the opening used to help in removal of the laminate form the base.



(a) (b)

Figure 3. (a) CAD model of laminated injection mould insert (16.5 H mm, 91 layers); (b) support base.

Test Procedure: Two wires of a J-type precision fine-wire (0.12 mm diameter) Teflon-insulated thermocouple were spot welded to the underside of the steel sheet individually so that they are nearly touching (Figure 4a). The wire leads were glued to the sheet to prevent them from moving during bonding. A channel (1.07H×1.5W mm) built within the laminate in order to accommodate the wires (Figure 4b) was modeled in CAD as part of the mould and built automatically. For each laminate which included the channel outline, the cut-out part of the sheet was manually removed. The data acquisition system comprised a NI-DAQ board 6035E, a dedicated temperature signal-processing module 5B37, and a LabVIEW v5.1 software. Measurements were collected at 50 samples per second.

(a) (b)

Figure 4. (a) thermocouple attached to the steel sheet; (b) laminate with thermocouple channel.

The process parameters varied included the roller load (L = 12, 25, 40, 51 kg), temperature (T_s = 120, 170, 220, 270, 320°C), and speed (V = 5, 10, 20, 40 mm/s). Thermocouples were embedded in 7th, 45th, and 87th layers. Only results for the 45th layer will be presented. Temperature was measured during the lamination of the sheet to which the thermocouple was attached as well as during the lamination of the subsequent sheets. To attach the sheet with the thermocouple, the film adhesive was spread manually on the previously built stack, its liner was peeled off, and the sheet with the thermocouple was placed so that the wires on its underside fit within the cutout slot. The roller temperature was allowed to stabilize for 20 minutes after the desired setting was indicated by the heater's controller. Then the roller was moved across the laminate surface while the data were collected.

Results and Discussion

Effect of Roller Load: The roller temperature and speed were kept at a fixed value, while the load was adjusted to observe the effect on the laminate temperature (Figure 5). The sharp peak corresponds to the roller passing directly over the thermocouple. Generally, higher pressure is expected to increase the heat transfer coefficient by increasing the contact surface area. We can observe this effect when the load is increased from lowest setting of 12 kg to the next higher setting of 25 kg. Further increase does not result in proportionate temperature rise. Therefore, only certain minimum pressure is needed to achieve good thermal contact. Load was set to 40 kg henceforth.

Effect of Roller Temperature and Speed: Good bonding requires certain heat, pressure *and* dwell time. Thus, the results are presented here as the average temperatures recorded between the time of reaching the peak temperature and five seconds later. As expected, increasing roller temperature setting, leads to proportionate increase in laminate temperature (Figure 6). The proportionality constant increases as the rolling speed decreases. The same information can be also plotted as a function of the roller speed (Figure 7) to obtain the "bonding curves" [7].

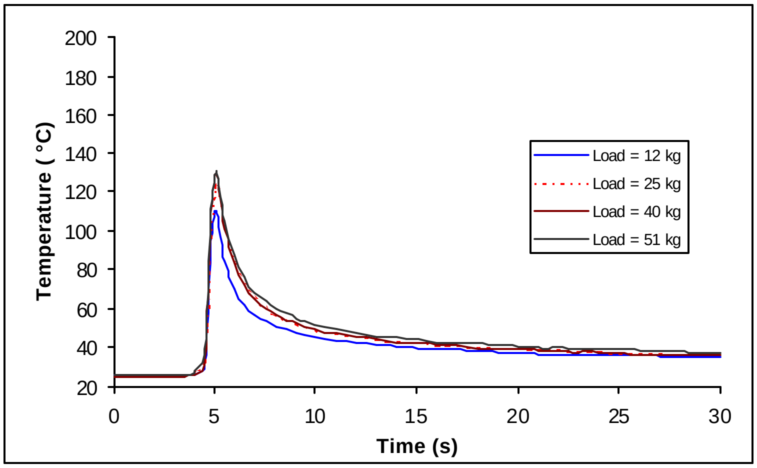


Figure 5. Effect of roller load on temperature (Layer = 45, T_s = 220 °C, V = 10mm/s).

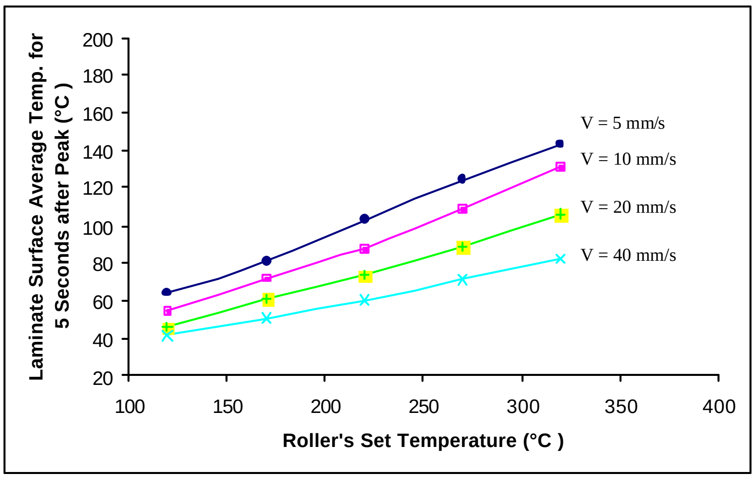


Figure 6. Effect of roller temperature on the time-averaged steel laminate temperature.

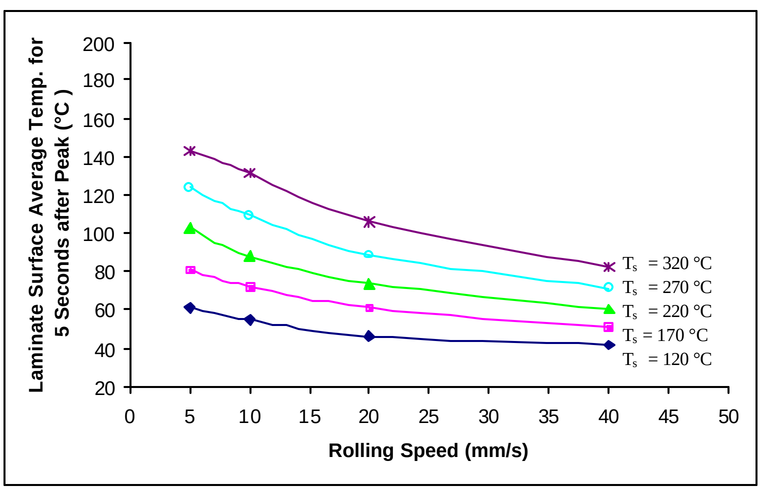


Figure 7. Effect of roller speed on the time-averaged steel laminate temperature.

Temperature during the Lamination of Subsequent Sheets: Temperature measurements were continued to be performed as the laminated object was built up above the 45th layer. In Figures 8 and 9, 1st layer refers to observations during the lamination of 45th layer (to which the thermocouple was attached), 2nd layer value to those during the lamination of the 46th layer and so on. Peak temperature still rises above 100°C for the next two layers after the 45th and then gradually declines. Thus, further significant heating of the adhesive occurs as new sheets are added which is similar to the results obtained in [10]. This implies that the adhesive in upper layers of the part will not have the same degree of heat activation as in the lower layers.

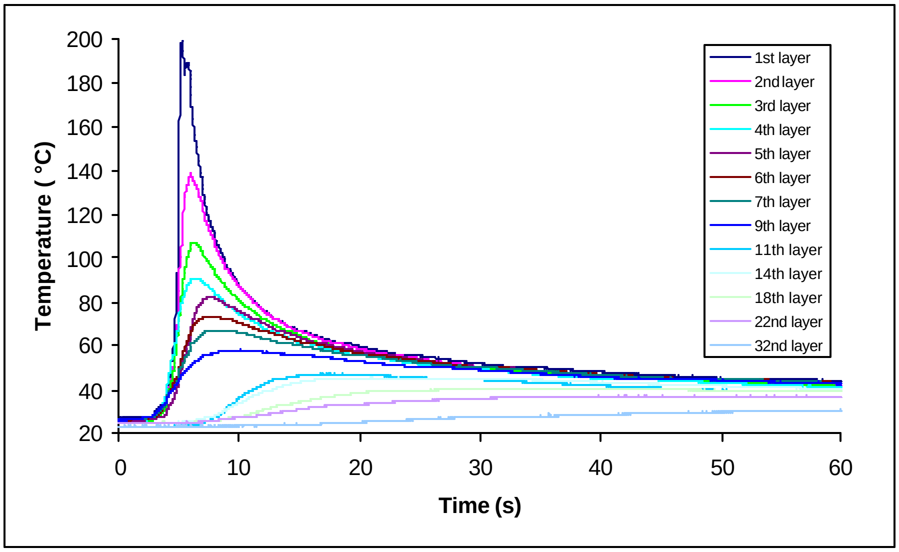


Figure 8. Temperature recorded during lamination of subsequent sheets (T_s=320°C, V=5 mm/s).

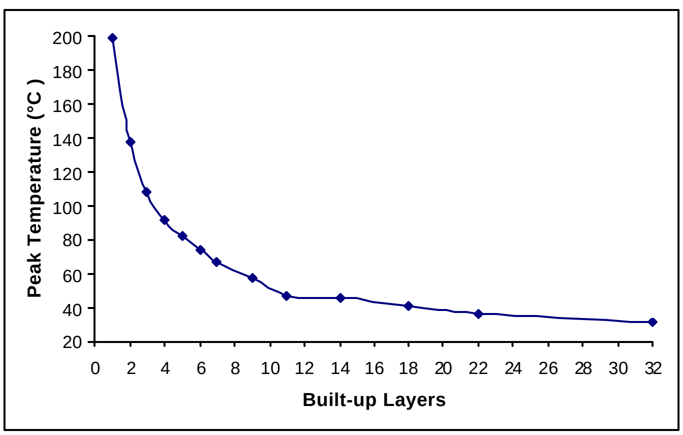


Figure 9. Peak temperatures observed during the lamination of subsequent layers.

Conclusions

Higher roller temperature, lower speed and higher roller pressure all resulted in increased heat transfer rate and therefore in higher surface temperature and longer duration of high temperature in the adhesive. As expected, the roller's temperature and speed are the most important factors. Once sufficient roller load was applied, further increases did not bring improved heat transfer to the laminate. The measurements also showed that the heat dissipates very quickly within the metal laminate. An enclosing chamber kept at elevated temperature would help to maintain the laminate at a higher temperature for a longer time. Further significant heating of the adhesive was found to occur for several subsequent laminations, which implies that process parameters may have to be adjusted for the upper part layer to assure the adhesive receives similar heat input as on the lower layers.

Acknowledgements

We gratefully acknowledge the financial support of Centre for Automotive Materials and Manufacturing, Ontario Innovation Trust, and Canada Foundation for Innovation. We also wish to express our thanks for assistance with thermocouple mounting to Mr. Claude Quenneville of Alcan Research Centre.

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