Bonding Methods for Laminated Tooling

by

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Abstract

Laminated tooling consists of an array of stacked laminations that are mechanically clamped or bonded together, depending on the requirements of the manufacturing process. Various manufacturing processes that can benefit from tooling constructed of laminations include sheet metal forming, thermoforming, composites molding, metal extrusion, injection molding, resin transfer molding, and compression molding. When bonding of the laminations is required (e.g., incorporation of conformal cooling passages for injection molding temperature control) then laminations can be joined together by diffusion bonding, brazing and using adhesives. However, for a tooling engineer to effectively design a laminated tool, the physical and mechanical properties of these joints must be known. Consequently, a set of experiments is outlined for determining the tensile, shear, and peel strengths, tensile and shear elastic moduli, thermal contact resistance, and specific permeability (for gasses or liquids) of the aforementioned bonded joints for both steel and aluminum laminations. Some preliminary results with aluminum and future work are presented.

Introduction

The concept of making intricate parts (e.g. transformer core, door lock assembly, gear) by assembling profiled or contoured laminations is a well-established manufacturing technique [15]. Laminated constructions have also been investigated, and successfully implemented by a few U.S. and Japanese companies [1,2] as a direct rapid tooling technique because of demonstrable advantages over other more conventional methods like CNC-machining and EDM. These advantages include the elimination of tooling accessibility problems, reduced limitations on die geometry, faster fabrication, and easier incorporation of conformal cooling passages [1,3]. However, laminated tooling techniques have not yet seen widespread use in industry. One of the main reasons for industry's hesitance to adopt laminated tooling is the problem of having to make a rigid tool out of an array of laminations. As shown in Figure 1, the two methods for accomplishing this are by mechanical means (i.e., clamping laminations together) and by bonding methods (i.e., welding, brazing, soldering, diffusion bonding, and adhesives).

This paper focuses on the latter method (i.e., bonding), especially for laminations with beveled edges as shown in Figure 1. Furthermore, it will address the problem of bonding laminated tooling in a more comprehensive manner than has been done previously. Consequently, previous work in this area will first be discussed. A survey of manufacturing processes that can benefit from using laminated tooling will also be mentioned along with process requirements that are needed for tooling design. This will be followed by discussion of common bonding techniques available for laminations made out of the two most common tooling materials used by industry, i.e., aluminum and steel. The complete experimental procedure of an ongoing research effort to characterize the mechanical and physical properties (i.e., tensile, shear and peel strengths, tensile and shear elastic moduli, thermal contact resistance, permeability, and dimensional changes) of bonded steel and aluminum laminations will be outlined. Finally, some preliminary results with aluminum will be presented.

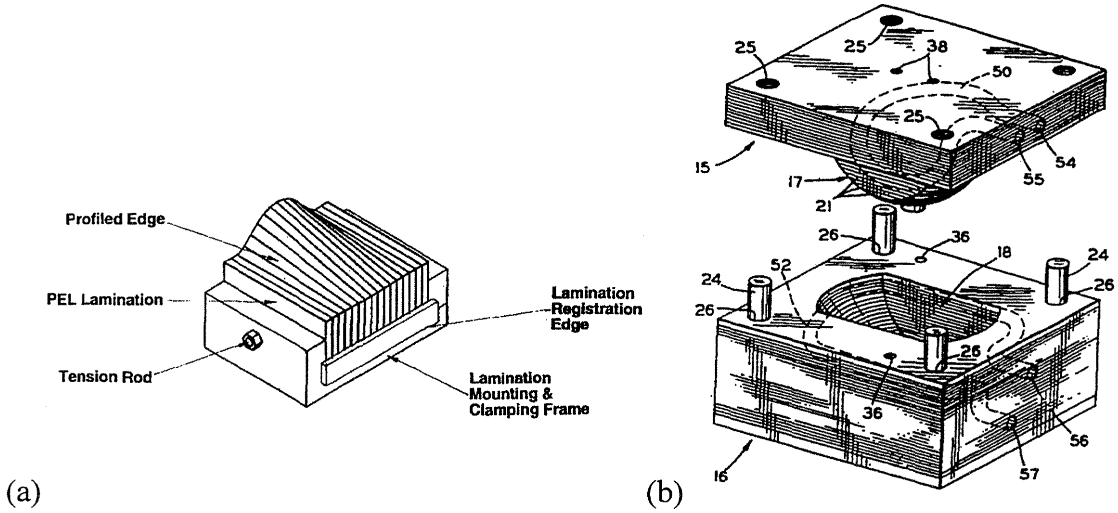


Figure 1 - Securing laminations together by (a) mechanical means and (b) with bonding methods.

Background

Several researchers have successfully used purely mechanical means to clamp die or mold laminations together for manufacturing production work. The manufacturing processes that tooling was created for include shoe making molds [4], sheet metal forming dies [1], polyurethane foam molds [5], and plastic injection molds [3,6].

Sometimes mechanical clamping of laminations is insufficient to meet the requirements of a particular manufacturing process. When this is the case, then the laminations will need to be bonded together into a solid die in order to meet these requirements (e.g., sealing required for conformal cooling passages, increased shear strength for sheet metal forming). Some preliminary work in lamination bonding includes laser welding lamination edges [7,8], brazing laminations together [9], bonding paper laminations together with a heated polymer layer [10], using adhesives for bonding plastic laminations [11], cementing steel laminations with a combination of adhesives and edge welding [12], diffusion and pressure bonding steel laminations together [13], and tack welding adjacent layers with an Nd:YAG laser [14]. Unfortunately, none of this previous work has investigated the specific mechanical and physical requirements (i.e., tensile, shear & peel strengths, tensile and shear elastic moduli, thermal contact resistance and permeability at various temperatures) for bonded joints that's required for a particular manufacturing process. Nor have any automated methods for bonding tool laminations (except for Ref. 10) been developed.

Candidate Manufacturing Processes for Bonded Laminated Tools

By virtue of previous research and a need for enhanced die or mold performance over that which is achievable using conventional fabrication means, the following manufacturing processes have been chosen as candidates for laminated tooling:

Sheet Metal Forming including cold and hot matched-die forming, drawing, and hydroforming. forming of sheet metal over a form die(s) of the desired shape. The metal is stretched to approximately 2% to 4% total strain, just beyond its yield point, to retain the contour of the die. High normal and shear forces on the die surface will tend to peel and shear bonds between laminations.

Thermoforming involves heating of a polymer sheet to its softening point, above the material's glass transition temperature (55-90°C), and drawing the pliable material against the contours (using vacuum or applied pressure) of the mold where it is held until cooled. Mild normal forces will tend to shear and pull bonds between laminations.

Composites molding involves curing of composite materials using a male or female mold at room temperature (25°C) and pressure or higher (autoclave curing). The pressures imposed by the autoclave is an overall external pressure, in essence, hydrostatic. Although in some cases, there is shrinkage involved with the heating of the composite. This can lead to some shearing loads on lamination bonds. Conformal cooling passages are sometimes used in composites molding.

Metal Extrusion involves forcing a billet of material (Aluminum, copper, magnesium, zinc, tin and their alloys) through a die opening, by way of a ram or a press, to produce a desired cross-sectional shape. Hot extrusion requires that the tool must be able to operate under severe conditions of temperature, pressure, and abrasive wear. Extrusion of metals creates very high shearing and normal forces on the inside surface of the billet container and die. Consequently, the lamination bonds will be subjected to tensile, shear and peel loads, regardless of lamination orientation. Cooling of the extrusion die with conformal cooling passages is not a common practice because of the difficulty of making these passages using conventional machining practices.

Injection molding involves melting and pressurizing granular or powdered thermoplastic polymer in a separate chamber and then forcing the molten polymer into a relatively cooler mold by way of a runner and injection system. It is in this "cooler" mold cavity that the part solidifies and forms. The high normal forces on the inside of the mold cavity (resulting from the high injection pressures) create very high tensile and peeling loads on the lamination bonds. Conformal cooling passages are commonly used in injection molding dies.

Resin transfer molding involves infusing liquid resin (i.e., thermosetting polymer) by vacuum, applied pressure or both into a pre-fabricated/assembled dry fiber preform contained by a mold. This molding process heats the granulated or powdered thermosetting polymers and while in the softened state, forced into the mold cavity through a runner system. The mild normal forces on the inside of the mold cavity create tensile and peeling loads on the lamination bonds. The mold is preheated to help in forming and curing thereby requiring conformal cooling passages.

Compression molding involves compressing a precise amount of thermosetting polymer or elastomer between heated mold halves and forcing the material to flow and conform to the shape of the mold cavity. Heating of the dies causes the thermoset to polymerize and cure into a solidified part. The normal forces on the inside of the mold cavity create tensile and peeling loads on the lamination bonds. Conformal cooling passages can be used to preheat the mold halves.

Important process information on these candidate processes for consideration with bonded joints include the maximum operating temperatures, internal or external pressures involved, thermal conductivity requirements, permeability requirements, and typical die materials used. The data for each of the candidate manufacturing processes is listed in Table 1 and discussed in the following section.

Table 1 - Pertinent data on the candidate manufacturing processes.

Manufacturing Process	**Maximum Operating Temp. (°C)**	**Typical Die or Mold Material**	**Maximum Operating Pressures (MPa)**	**Thermal Conductivity Requirements for tool.**	**Permeability Requirements**	**Applicable Bonding Methods**	**Worked Material**
Sheet Metal forming	25	kirksite, Steel, Alum., Epoxy	7.0	low	none	diffusion, brazing or adhesives	sheet steel or aluminum
Thermoforming	55-90	Steel, Alum., Wood	0.8	low	vacuum, conformal cooling	diffusion, brazing, or adhesives ⊗⊗	plastics *
Metal extrusion	500	Tool Steel	60	high	cooling	diffusion, brazing	aluminum
Injection molding	100 to 150	Steel, Alum.	14 to 170 ⊗	high	selective heating & cooling	diffusion, brazing, or adhesives ⊗⊗	plastics **
Resin transfer molding	200	Steel, Alum.	0.3	high	vacuum, heating	diffusion, brazing, or adhesives ⊗⊗	plastics ***
Compression molding	200	Steel, Alum.	14 to 170 ⊗	high	cooling	diffusion, brazing, or adhesives ⊗⊗	plastics +
Composites molding	150	Steel, Alum.	1.4 ◊	medium to high	vacuum, heating	diffusion, brazing or adhesives	composites ++

*	uses both thermosetting (T/S) and thermoplastic (T/P) polymers but generally T/P
**	uses T/P only
***	uses T/S only
+	uses both T/P and T/S with equal efficiency
++	as in fiberglass based composite polymers along with various graphite based epoxies and T/S
⊗	depending on the material
◊	under extreme conditions, though usually hydrostatic at 2.4 MPa
⊗⊗	adhesives to some extent depending on the pressures necessary to form the material properly

Lamination Bonding Methods

There are several methods suggested for bonding steel to steel, and aluminum to aluminum including diffusion bonding, brazing, and joining with adhesives [16]. Each of the aforementioned bonding methods is discussed below:

Diffusion bonding involves the filling of voids (asperities) at a bond interface by migration of molecules. Specifically, the diffusion kinetics at the bond are accelerated by applying the appropriate pressure and temperature to the lamination joint over a period of time. For example, Nakagawa et al. [13] diffusion bonded 55 sheets of cold-rolled steel by heating them together in a vacuum at a temperature 1100°C followed by the application of pressure of 5.9 MPa for one hour. Advantages of this process include no visible bond line, a clean fluxless process, strength of the bond up to 100% of the parent material strength, and no significant thermal contact resistance. Disadvantages include the limited application of this process to specific combinations of materials (e.g., aluminum to aluminum doesn't work), mild shrinkage (400 microinches at a joint), need for a hot press, need for a material that forms voids, low tolerance of poorly mating surfaces, and high processing temperatures (roughly $2/3^{rds}$ of the parent material's melting point). As a result, diffusion bonding is mainly limited to steel (and titanium) laminations [17].

Brazing involves introducing molten filler metal (e.g., copper, silver, nickel) between laminations to wet the mating surfaces of the joint and formation of a meturallurgical bond. Bonding is achieved by diffusion of the filler material into the parent material and recrystallization of the filler material around the asperities thereby creating an enhanced surface area adhesion. Steel on steel requires a flux (i.e., non-metallic chemical compound) to clean the surface of oxides and other contaminants, facilitate easy wetting of the surface and then evaporates. Brazing is done at 450°C and above, and therefore is not recommended for relatively low melting point metals (e.g., aluminum). Advantages of brazing over other bonding methods include minimal effect on the base material composition, large bonding area for evenly distributing stresses, higher tolerance for mismatched surfaces than diffusion bonding because voids and gaps are filled. Disadvantages include the need for the joints to have controlled gaps or clearance, and fluxing. Brazing is mainly limited to steel.

Bonding with adhesives involves applying the adhesive material between the surfaces and letting it cure.

Soldering and edge welding are not being considered as suitable bonding methods for the following reasons:

Soldering is similar to brazing except that wetting of the filler material (e.g., tin, lead and their eutectic alloys) on the base material occurs at below 450°C. The measured strength is comparable to adhesive bonding but the processing is more difficult because gaps or clearance is needed between laminations. Initial experiments have shown that using soldering to bond the aluminum pieces together with minimal clearance led to poor bonding. Messler [16] suggests that adhesives would be a better choice than soldering because gaps won't need to be maintained with the former.

Welding of the lamination edges is not being considered because the piece-wise continuous surface afforded by the beveled edges would be significantly altered and secondary machining operations would be required as evidenced by Azuma [7], Pridham and Thomson [8] and Kunieda et al. [12].

Experimental Procedures

Various experiments being performed will establish the important mechanical and physical properties of various types of bonded lamination joints. Since the joints will add some degree of elasticity to the die, tensile and shear elastic moduli are important for the die designer to know. The types of laminated die failures that can occur due to the manufacturing processes listed in Table 1 are tensile (Fig. 2a), shear (Fig. 2b), and peeling (Fig. 2c), either separately or in some combination. For this reason, tensile, shear and peel strengths are also useful to know. Since the bonded interfaces provide a resistance to thermal conduction in the direction perpendicular to the bond plane, as shown in Figure 2d, the thermal contact resistance for a particular type of bond is also important. The degree of fluid (i.e., hydraulic oil or air) permeation in the lamination bonds is important to know when conformal cooling with pressurized fluid (e.g., injection molding), as shown in Figure 2e, or drawing of a vacuum (e.g., thermoforming) is being considered. For this reason, the specific permeability for various bonds is being determined. Finally, the minute separation of the bonded laminations is being measured to quantify the lateral expansion of a laminated die after bonding.

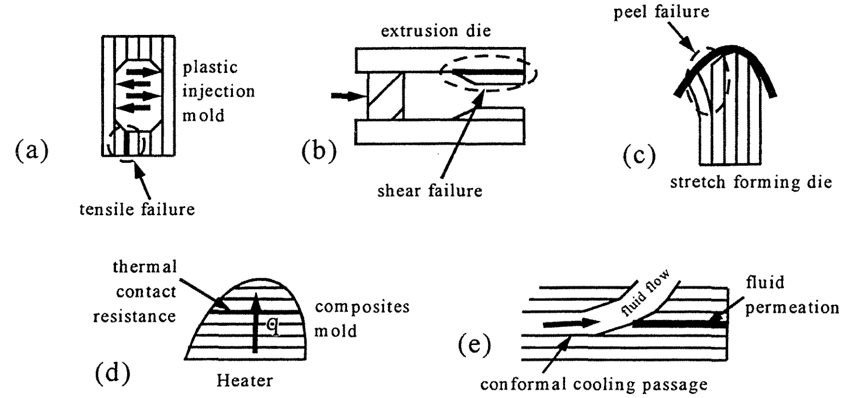


Figure 2 - Examples of (a) tensile (pull) failure, (b) shear failure and (c) peel failure (d) thermal contact resistance and (e) fluid permeation of various laminated dies and molds.

Tensile Strength (σ_t in MPa) and Tensile Elastic Modulus (E_t in MPa) - The tensile test is perhaps one of the most common of all strength tests. The basic premise of this test is to pull (using a Universal Testing Machine) a bonded specimen of area (A_{bond}) and thickness (t), as shown in Figure 3a, perpendicular the bonded surfaces and measure the elongation ($\delta_{failure}$) and force ($F_{failure}$) of the joint at failure with respect with its original position and unloaded state. The tensile forces applied must be uni-axial in order to achieve pure tension. This test is based on ASTM Designation: D 2095-72 standard test method. Assuming that the bond material obeys Hooke's law up to failure, then the tensile strength and elastic modulus are calculated using the following equations:

$$\sigma_t = \frac{F_{failure}}{A_{bond}} \text{ and } E_t = \frac{F_{failure} \cdot t}{\delta_{failure} \cdot A_{bond}} \tag{1}$$

Shear Strength (τ_s in MPa) and Elastic Modulus (G_s in MPa) - The test being used to measure the shear strength and elastic tensile modulus of a lamination joint is a modification of ASTM Designation: D 2295 - 92 standard test method. The basic premise of this test is to pull a lapped joint of thickness (t), as shown in Figure 3b, parallel to the bonded surfaces and measure the elongation ($\delta_{failure,s}$) and force ($F_{failure,s}$) of the joint at failure with respect to its original position and unloaded state. Assuming that the bond material obeys Hooke's law up to failure, then the shear strength and elastic modulus are calculated using the following equations:

$$\tau_s = \frac{F_{failure,s}}{A_{bond}} \text{ and } G_s = \frac{F_{failure,s}}{A_{bond} \cdot \tan^{-1}\left(\frac{\delta_{failure,s}}{t}\right)} \tag{2}$$

The small angle approximation for the shearing strain (i.e., $\gamma = \frac{\delta_{failure,s}}{t}$) is not used in determining G_s because $\delta_{failure,s}$ is typically much larger than t.

Peel Strength (α_p in $\frac{N}{m}$) - The T-peel test for determining the peel strength of a lamination joint of width (w) is based on ASTM Designation: D 1876-93 standard test method. Peel strength is a measure of a joints resistance to localized stresses and failure by progressively opening the adhesive face normal to its bond line. The basic premise of this test is to pull a T-joint, as shown in Figure 3c, normal to and at one edge of the bonded surfaces and measure the average force, i.e., $F_{ave,p} = \frac{F_{\max,p}+F_{\min,p}}{2}$, of the joint at failure with respect to its unloaded state. Peel strength is calculated using the following equation:

$$\alpha_p = \frac{F_{failure,p}}{w} \tag{3}$$

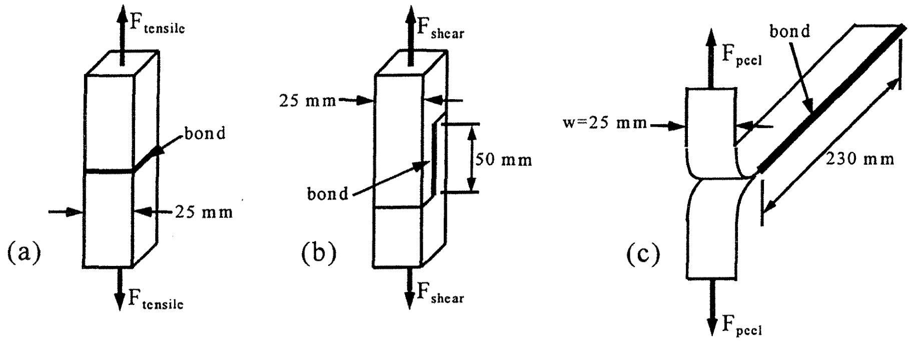


Figure 3 - Specimens for measuring joint strength and elastic modulus when subjected to (a) tensile, (b) shearing and (c) peeling loads.

To quantify the effect of elevated temperatures (particularly the maximum values listed in Table 1) on bond strengths and elastic modulus, the tests will be run at room temperature (i.e., 24°C), 100°C, and 200°C and 1000°C (diffusion-bonded steel only). As shown in Figure 4, uniform heating of the specimens is achieved by wrapping resistive-type heating tape around the bonded area. Using heating tape is an inexpensive means for heating the localized area up to 200°C without interfering with the failure mode of the specimen. The temperature of the bonded area is monitored by a digital thermometer using a K-type thermocouple in direct contact with the test specimen. This simple arrangement has been shown to maintain a uniform temperature to within ±3°C. These heated specimens were pulled apart on a Universal Testing Machine at a rate of 25 mm/min.

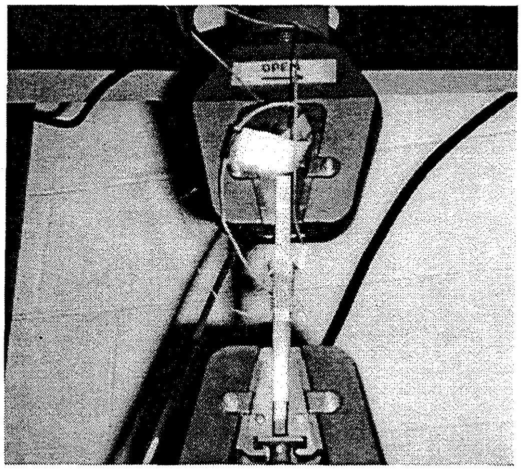


Figure 4 - Simple configuration for uniform heating of test specimens.

The *thermal contact (conductive) resistance per unit area* ($R''_{t,c}$) of the various joints will be measured using the apparatus shown in Figure 5a. Because of the symmetrical nature of the heating element sandwiched between identical bonded metal laminations, the heat rate in the positive and negative x-directions is assumed to be the same (i.e., $\frac{q_x}{2}$). The equation for determining the value of this contact resistance is:

$$R''_{t,c} = 2\left[\frac{A(T_i - T_s)}{q_x} - \frac{L}{k_m}\right] \qquad (4)$$

where:
A = cross sectional area of bonded joint
T_i = temperature at heating element
T_s = temperature at outside surface
q_x = total heat rate of heating element
L = thickness of single lamination
k_m = thermal conductivity of lamination material.

The *specific permeability* (*k*) of a bonded joint (i.e., how well it seals) will be measured using the experimental arrangement shown in Figure 5b. Assuming that the bond has some degree of permeability, the test fluid used is incompressible, and fluid flow through the bond is laminar, the specific permeability of the bond material is based on the Darcy's equation

$$k = \frac{-Q\mu h}{A_f(p_i - p_o)} \qquad (5)$$

where:
Q = volumetric fluid flow rate (measured)
μ = viscocity of the fluid
h = width of the bond
$A_f = \pi(d_i + h)t$ = total cross-sectional area of bond perpendicular to the direction of flow
t = thickness of the bond
p_i = internal pressure of the bonded cylinder and
p_o = atmospheric pressure.

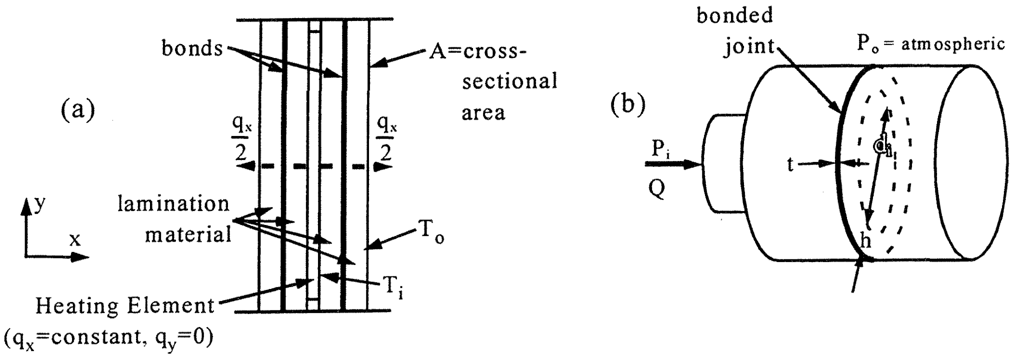


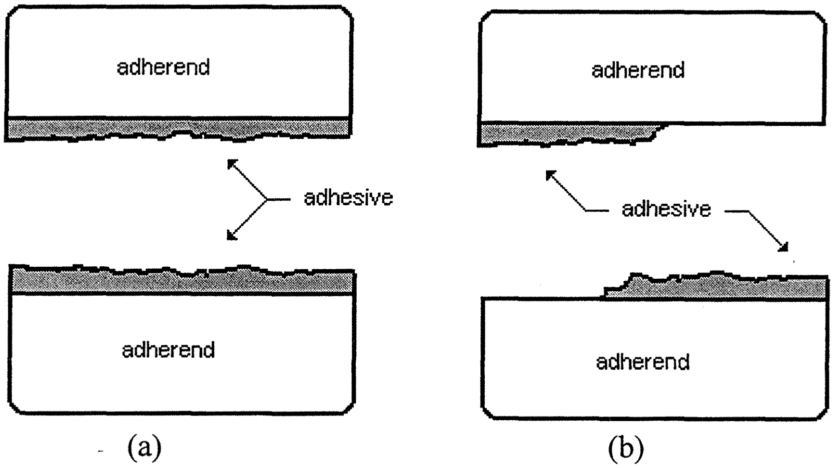
Figure 5 - Experimental set-ups for determined (a) thermal contact resistance and (b) specific permeability of a bonded lamination joint.

Preliminary Experimental Results

Some preliminary results are described for adhesive bonding of aluminum laminations. Four high strength, high-temperature adhesives (representative of the wide variety available) were tested including Devcon Plastic Steel® epoxy, Cotronics® Alumina-based Adhesive, Dymax 846® and 828® epoxy. Each adhesive consists of two parts, i.e., an activator (or hardener) and the base adhesive. The Devcon Plastic Steel adhesive is a metal-filled epoxy which cures to full strength at room temperatures in 24 hours, or at 120°C in 15 min and cooled back down to room temperature in 1 hour. The Cotronics adhesive system is a ceramic based adhesive that uses alumina oxide as a base adhesive. The alumina bonds to the oxidizing layer on the aluminum and creates the bond. The alumina based adhesive cures at room temperature for a 24 hour period or at 120°C for 2 hours. With the alumina based system, fast heating will create bubbles within the adhesive joint and must therefore be avoided. Dymax 828 and 846 adhesives are polyurethane oligomer-based mixtures that can cure at room temperature in 12 hours or at 100°C in 10 minutes. Devcon is widely-available and low cost, Cotronics gives a high temperature performance, and Dymax gives the lower viscosity and is the most elastic of the group, achieving elastic shear moduli of 9.1 and 7.5 MPa.

The tests show that there is a correlation between the distribution of the adhesive on the surface and the bond strength. A good distribution of an adhesive is when the adhesive has spread evenly and no voids are present. According to test data, the better and more even the distribution, the greater the failure strength. All samples broke in either a full cohesive failure (see Fig. 6a) or a partial cohesive failure (see Fig. 6b), suggesting strong bonds at the adhesive/adherend interface. Full cohesive failure mode suggests that the adhesive was used to the fullest, while partial cohesive failure suggests one of the following; sample surface was under-prepared (i.e., the surfaces were not completely free of contaminants), gap spacing between surfaces was uneven (attributing to thicker adhesive sections), or contaminants were introduced during processing (or heating).

The shearing experiments for every adhesive have shown that the slope of the shear force versus bond elongation curve is basically linear, i.e., obey Hooke's law, up until the point of failure. This implies that Equation 1 is valid for adhesive bonding. The shearing force and elastic moduli are calculated using Equ. 1 and listed in Table 2.



(a) (b)

Figure 6 - Examples of (a) full cohesive and (b) partial cohesive failure for shear tests.

Table 2 - Shear test results for aluminum bonded with adhesives at room temperature and .

Adhesive used	Test temp. (°C)	Adhesive thickness (mm)	Failure Load (kN)	Shear Strength (MPa)	Elongation at Failure (mm)	Shear Modulus (MPa)	Cohesive Failure Mode
Devcon	24	0.19	13.0	10.1	2.1	6.8	Partial
Dymax 828	24	0.18	17.5	13.6	2.4	9.1	Full
Dymax 846	24	0.23	14.1	10.9	2.1	7.5	Full
Cotronics	24	0.47	2.47	1.91	0.38	2.8	Partial
Devcon	100	0.14	1.65	1.28	0.25	1.2	Partial
Dymax 828	100	0.24	10.4	8.06	1.9	5.6	Full
Dymax 846	100	0.21	9.61	7.45	1.8	5.1	Full
Cotronics	100	0.29	2.78	2.16	0.53	2.0	Partial

Future Work

The design and performance issues have been identified for laminated tooling and experimental set-ups have been devised for quantifying pertinent physical and mechanical properties. For the σ_t, E_t, τ_s, G_s, and α_p experiments, aluminum laminations will be tested at 25, 100 and 200°C. In addition to measurements at these temperatures, diffusion-bonded and brazed steel will be tested at 500°C which is the nominal operating temperature for metal extrusion. $R''_{t,c}$ and k will be measured at 25, 100 and 200°C for both steel and aluminum. As a comparison with bonded laminations, $R''_{t,c}$, and k will be measured for laminations that are clamped together under uniform pressure. Experimental results will be compared with theoretical models (e.g., Stefan's equation for predicting adhesive bond strength) whenever possible.

Following this experimental work, several examples of how the data can be used in designing laminated tooling for each of the aforementioned manufacturing processes will be developed. In addition, several techniques for automating the lamination bonding process (e.g., dip brazing, applying adhesive with a stationary roller) are being devised and will be demonstrated.

Acknowledgements

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