Laser Beam Weld Bonding of AA5754 for Automobile Structures

There are benefits in both static and dynamic mechanical properties when welding is combined with adhesive bonding

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ABSTRACT. Combining spot welding with bonding using a structural adhesive in the hybrid process of weld bonding is known to result in synergistic benefits in joint static and, especially, dynamic mechanical properties. Here, a laser beam source was substituted for a more traditionally used resistance welding source to produce spot welds either through the adhesive or in gaps in the adhesive in a study of the weld-bonding of AA5754 for application in the assembly of automobile body and underbody structure. Static shear, coach (T-coupon) peel, and shear fatigue were all assessed in various combinations of sheet thickness, pretreated (i.e., dry lubricant coated or uncoated) conditions, and testing temperatures.

Introduction

In response to pressure from the Environmental Protection Agency (EPA), as well as consumers, for more fuel-efficient and environmentally friendly automobiles, manufacturers are looking at alternative materials of construction to reduce vehicle weight. Weight is the key to fuel savings because a 10% reduction of weight yields a 6–8% improvement in fuel economy (Ref. 1). Aluminum alloys are leading candidates because of their inherently low density and superior corrosion resistance (compared to steels), greater design flexibility due to ease of forming and diversity of forming processes (compared to reinforced plastics), aesthetic appeal (at least when unpainted), and 100% recyclability (offering environmental friendliness at a premium scrap value) (Ref. 1). The one-third density of aluminum alloys vs. steels (i.e., 2.8 vs. 7.8–7.9 g/cm^3) has been purported to afford as much as a 40% "body-in-white" (BIW) weight savings (Ref. 2). However, to replace steel, the current "workhorse" material of construction for automobiles, aluminum alloys have to be equally amenable to modern automobile production methods, including assembly while traveling along a production transfer line with many assembly operations being automated, frequently using robots. With speed and efficiency being critical to production economy, a fast, reproducible, and reliable method for joining is as essential as joints that provide structural integrity under a complex combination of static and dynamic loads.

The Challenges of Joining Aluminum Structures

As is so often the case in life, the attractive properties of aluminum alloys as a structural material are accompanied by their special challenges to automated automobile assembly, especially to traditional welding methods (e.g., resistance spot welding) long used by the industry. Aluminum and its alloys are extremely reactive with air and quickly form a tenacious, highly refractory oxide (Al_2O_3) outer layer on all exposed surfaces. Pure aluminum has a melting point of about 660°C (1200°F), while its oxide has a melting point of about 1650°C (3000°F), thereby persisting even in the melt. Furthermore, aluminum's oxide is both electrically and thermally insulative. Hence, it presents a barrier that must be penetrated before the base metal can melt during welding to achieve the metal-to-metal (part-to-part) continuity that is required to produce a weld (Ref. 3).

Resistance welding, the process that predominates in vehicle assembly throughout the automobile industry, becomes particularly difficult with aluminum alloys (Ref. 4). Passing current into the aluminum alloy parts to join them with the desired spot weld at part-to-part interfaces becomes very difficult without careful, time-consuming, and expensive chemical and mechanical cleaning reasonably soon (ideally, just) before welding to prevent reoxidation/recontamination. High contact resistance between the copper (or copper-alloy or composite) welding electrodes and the oxidized aluminum alloy, together with aluminum oxide's high melting point compared to copper's (i.e., 1600°C or 3000°F compared to 1035°C or 1985°F, respectively), leads to unwanted melting at the electrode-to-weldment interface while current is applied to slowly break through the insulative oxide.

While new Cu-based electrode compositions show promise of dramatically extending electrode life in the laboratory or under controlled tests, this is not the case in production. Controlled tests tend to employ flat, close-fitting lap joints, the shorter welding cycles allowed by such joints, and electrodes that are optimally sized for each particular combination of joint element gauges and desired spot size. All of these factors allow the welding heat to be minimized and extend electrode life to thousands of welding cycles or spot welds before electrode change-out, even without periodic tip dressing. Welding in actual production, on the other hand, generally results in electrode life of hundreds of welding cycles or spot welds, at best, with built-in automatic dressing of electrode tips often occurring every 20 weld-

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KEY WORDS

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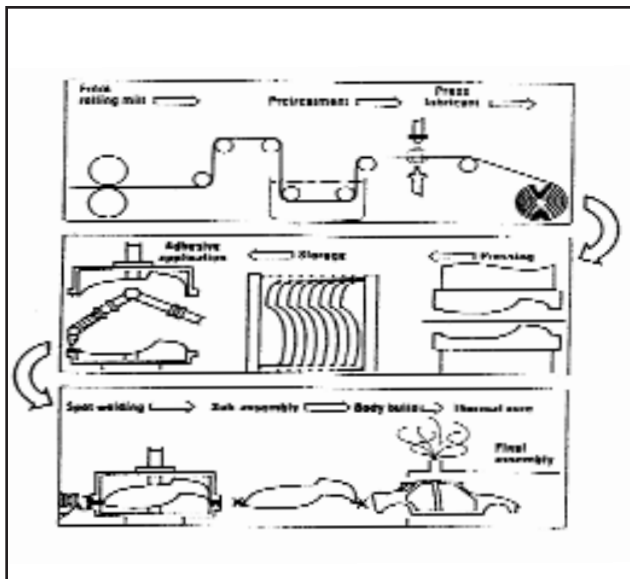Automobile Assembly

Fig. 1 — Aluminum Company of Canada (Alcan) ASVT manufacturing system using weld-bonding.
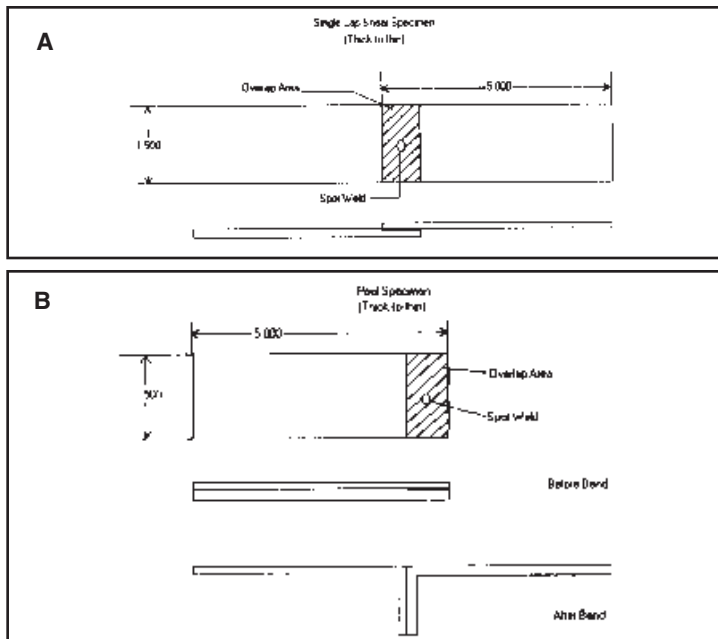

Fig. 2 — Test specimen geometry. A — Single-lap shear; B — coach (T-coupon) peel.

ing cycles or so. Less-tight-fitting lap joints between formed sheet metal parts, often with complex curvatures, and the need for larger electrodes to enable multiple gauge combinations (typical of most vehicle assembly) to be handled without changes, demand higher welding currents and longer welding cycles; both of which combine to increase heat at the electrode-to-aluminum workpiece interface. The result of these production realities leads to 1) electrode sticking and 2) accelerated wear, as well as 3) Cu-contamination of the aluminum alloy (with possible cracking) (Ref. 5). At the part-to-part interface, the resulting spot weld also frequently contains porosity from absorbed moisture typically associated with the oxide, and brittle (and embrittling) inclusions of the oxide itself.

Another issue with welding aluminum alloys is their high thermal conductivity. Heat is quickly dissipated through the metal, causing difficulties with localized melting and a tendency for cracking upon solidification, which always takes place more rapidly than in less thermally conductive metals. When attempting to weld aluminum alloys, additional heat must be added to achieve melting, and cooling after welding must be controlled, typically using preheating and postheating techniques in the form of added current pulses during resistance spot welding. (Ref. 6).

As a result of all of the above, the resistance spot welding process found so amenable to welding steel automobiles poses challenges that are, from a practical, even if not theoretical, standpoint, insur-

mountable for the automobile industry at large. Fortunately, there are other viable ways to join aluminum and its alloys.

Weld-Bonding as an Alternative for Joining Aluminum

Extensive experience in the aerospace industry over several decades has shown that aluminum alloys are especially suited to joining by adhesive bonding (Ref. 7). Adhesive bonding is the process of employing substances (i.e., chemical agents) capable of holding materials together by surface attachment forces (Ref. 8). Adsorption, diffusion, electrostatic (coulombic) attraction, and mechanical interlocking all contribute to one degree or another, depending on the active bonding agent (i.e., adhesive) and substrates (i.e., adherends) (Refs. 8–10).

Adhesives and adhesive bonding offer a number of advantages, including 1) excellent strength in shear (due to both the large bond surface area normally involved and the viscoelastic nature of most adhesives), 2) uniform distribution (i.e., spreading) of loads and softening of stress concentrations (compared to fastened or spot welded joints), 3) excellent fatigue resistance (largely due to the viscoelastic nature of most adhesives, and attendant self-healing of cracks, as well as reduced stress concentrations from load spreading), and 4) good energy absorption (from impact and/or vibrations). Other associated (secondary or designed in) properties can include sealing (against fluid leakage), and thermal and electrical insulation, elastic-

ity, and smoothing of contours (especially in joint areas) (Refs. 8, 10).

Despite these numerous advantages, there are shortcomings, if not disadvantages, to the adhesive bonding process. These include 1) low peel strength under out-of-plane loads (largely due to the low inherent strength of adhesion between adhesive and adherend or substrate), 2) limited tolerance of low (generally much below 0°C) or even moderately high (generally above 200°C) temperatures, 3) short shelf life, 4) short working life, and 5) tendency of fumes/odors to be toxic, beyond just being unpleasant (Refs. 8, 10).

As stated at the beginning of this section, there are many different and diverse adhesives that work well with aluminum and its alloys including, but not limited to (Refs. 8, 10), modified epoxies, modified phenolics, epoxy-phenolics, neoprene-phenolics, second-generation acrylics, cyanoacrylates, silicone rubbers, nitrile-phenolics, vinyl-epoxies, and polyurethanics.

Such a wide choice offers opportunities to achieve desired properties and performance for a wide variety of loading, environmental, and production manufacturing conditions. It also offers considerable challenges to both design and process engineers.

An attractive, compromise joining process for the assembly of aluminum structures in automobiles is weld bonding. Weld bonding is defined as "a spot welding process variation in which the spot weld strength is augmented by adhesive at the faying surfaces" (Ref. 9). In general
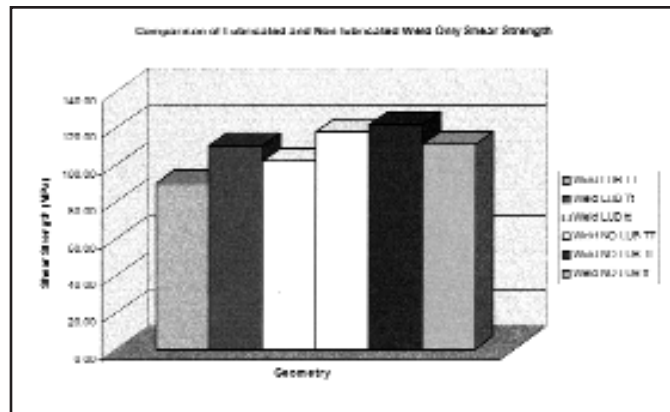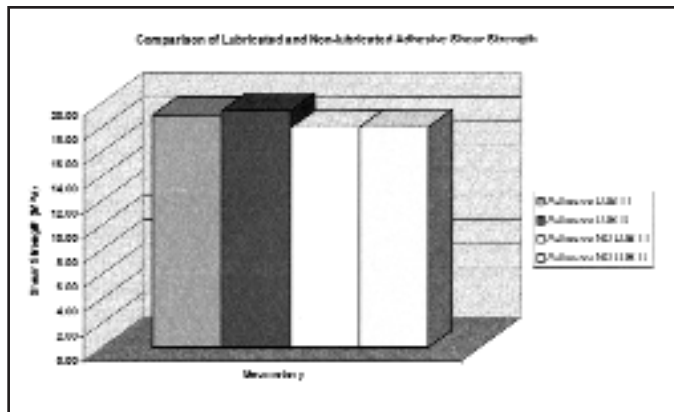
Fig. 3 — Graph showing lubricant effect on adhesive-only test results of static shear strength.

Fig. 4 — Graph showing lubricant effect on weld-only test results of static shear strength.

terms, it is the combination of adhesive bonding with a welding process to gain advantages of each joining method (in the form of a hybrid method), and, ideally, some unique advantages through a synergistic effect (Ref. 11).

Alcan (Aluminum Company of Canada) has explored the weld-bonding process for an automobile production line with its ASVT process — Fig. 1. First, adhesive is applied to preformed, chemically pretreated aluminum panels. The panels are then spot welded together with the spot welds acting as "clamps" or "tacks" for the joints, preventing the panels from shifting throughout further production processing. Finally the heat-activated adhesive is thermally cured in an oven at the end of the production line (Ref. 2). The adhesive provides shear strength, while the weld protects the joint from out-of-plane loads.

There are several particularly interesting potential benefits for weld-bonding. The static shear strength of the joint can be reasonably expected to increase along with the peel strength; with spot welds carrying out-of-plane loads to protect the adhesive from peeling. Fatigue life of the joint can be expected to increase because of the presence of the adhesive; with the adhesive spreading the loading around the spot welds to soften stress concentrations. Synergistic effects between the adhesive and the welds can thus be present. Load transfer is vastly improved throughout the joint. The adhesive also provides energy absorption (which improves crash worthiness), sealing and corrosion resistance (which extends vehicle life in the face of environmental factors), vibration damping (which contributes to improved ride quality by reducing harshness and noise),

and smooth contours (which contributes to appearance/aesthetics) (Refs. 8, 12).

Overall, weld-bonding could allow the automobile industry to optimally join aluminum alloys, which are inherently much more difficult to spot weld than steels, but relatively easy to adhesive bond. The purpose of this study was to assess the use of laser (spot) weld-bonding, because of numerous attractive characteristics and qualities of laser beam welding, including 1) precise control of energy input level and weld placement, 2) suitability for use in a normal production plant environment (i.e., open air), 3) amenability to automation using fiber-optic delivery with robotic end-effectors, and 4) use of a central power source and beam splitting (Ref. 3).

Experimental Procedure

Test Coupon Preparation

Aluminum alloy AA5754, provided by Alcan in 4- x 1-ft (i.e., 130- x 30-cm) panels mechanically sheared from larger sheets, was used throughout the study. Ta-

Table 1 — Composition of AA5754

Alloy	Spec Source	Limits	Cu	Fe	Mg	Mn	Si	Ti	Cr	Zn
5754	AA	Max.	0.1	0.4	3.6	0.5	0.4	0.15	0.3	0.2
		Min.			2.6					

Table 2 — Mechanical Properties (Typical Values) of AA575-O (Annealed Condition)

	UTS	UTS	0.2% Proof Stress		
Alloy and Temper	MPa	ksi	MPa	ksi	Elong %
5754-O	225	32.6	105	15.2	26

bles 1 and 2 give the alloy's composition and mechanical properties, respectively. A proprietary water-soluble dry lubricant designed especially for use with adhesives was preapplied to the aluminum alloy sheet at Alcan. Two thicknesses of 2.08 mm, referred to as "thick," and 1.03 mm, referred to as "thin," were used for three different mechanical property tests: 1) single-lap static tensile shear (Fig. 2) to ASTM D1002-99, 2) coach (T-coupon) peel (Fig. 2) to ASTM D1876-99, and 3) single-lap tensile shear fatigue to ASTM D3166-99. The purpose of single-lap static tensile shear testing is to assess joint strength under static in-plane loading, while the purpose of single-lap tensile shear fatigue testing is to assess joint strength (or life at a given stress level) under cyclic loading. The purpose of coach (T-coupon) peel testing is to assess out-of-plane (peel) strength, and to give an indication of the joint's ability to absorb energy upon impact, say during a crash.

For all three tests, appropriate-sized sheared blanks[1] were laser beam spot welded only; adhesive bonded only; or

1. All blanks were 38.1 mm (1.5 in.) long, with static tensile shear and tensile shear fatigue coupons overlapped at opposite ends of the two pieces making up the cooupon, and coach peel coupons stacked as pairs face to face. Overlap was chosen to ensure failure occurred in shear in the joint, not by overload in the base metal. Figures 2A and 2B show the two specimen designs.
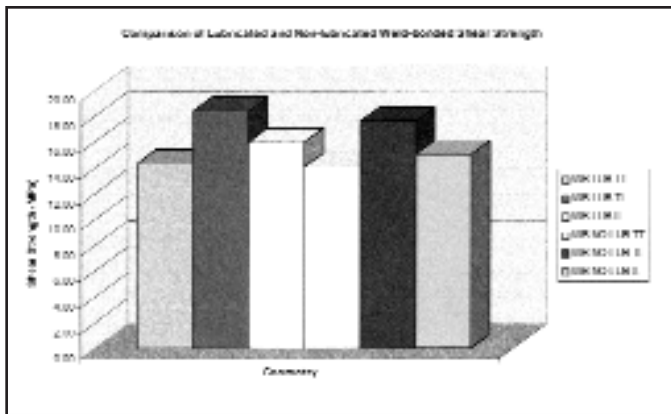
Fig. 5 — Graph showing lubricant effect on weld-bonded test results of static shear strength.
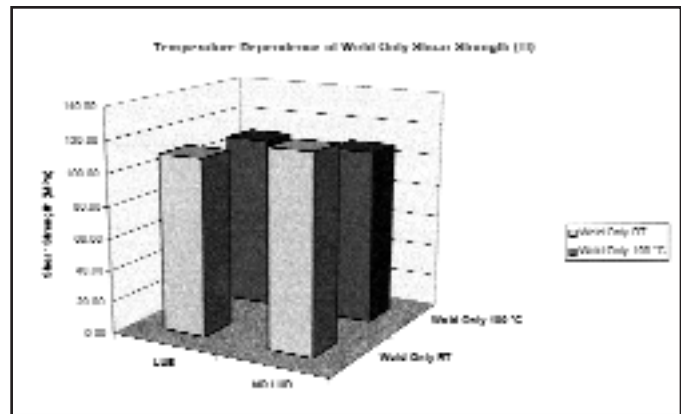

Fig. 6 — Graph showing temperature effect on weld-only static shear strength.

Table 3A — Full Test Matrix for the Study; Part A, Static Tensile Shear

Single Lap Shear Test Matrix

Sample Type	Orientation	Overlap (mm)	No. at RT	No. at 100 °C	No. Extra	No. Total
Adhesive, lubricant	thick thick	15	3	3	1	7
	thin thick	8	3	3	2	8
Adhesive, no lubricant	thick thick	15	3	3	1	7
	thin thick	8	3	3	2	8
Weld, lubricant	thick thick	15	3		1	4
	thin thick	8	3	3	2	8
	thin thin	8	3		1	4
Weld, no lubricant	thick thick	15	3		1	4
	thin thick	8	3	3	2	8
	thin thin	8	3		1	4
Weld, through adhesive lubricant	thick thick	15	3		1	4
	thin thick	8	3	3	2	8
	thin thin	8	3		1	4
Weld, through adhesive, no lubricant	thick thick	15	3		1	4
	thin thick	8	3	3	2	8
	thin thin	8	3		1	4
Weld, gap in adhesive, lubricant	thick thick	15	3		1	4
	thin thick	8	3	3	2	8
	thin thin	8	3		1	4
Weld, gap in adhesive, no lubricant	thick thick	15	3		1	4
	thin thick	8	3	3	2	8
	thin thin	8	3		1	4
					Total	126

No. of thick pieces 140.
　No. with 4.625 in. to hole 76.
No. with 4.4865 in. to hole 64.
No. of thin pieces 112.
　All with 4.4865 in. to hole.

laser (spot) weld-bonded in thin-to-thin, thin-to-thick, and thick-to-thick combinations, with the producer-applied lubricant (designated "lubricant") or with that lubricant removed by washing in clean warm water (designated "no lubricant"). Some tests (e.g., static tensile shear and coach peel) were performed at room temperature and others at 100°C to test for the effect of temperature on the joints in inherently warmer structures (e.g., around the engine compartment). Table 3, consisting of Parts A, B, and C, gives the full test matrix for the study.

Welded-Only Test Specimen Preparation

Combinations of thin-to-thin, thin-to-thick, and thick-to-thick blanks in lubricant and no-lubricant conditions were spot welded using a 1700-W Convergent-Prima Arrow Ultimate CO_2 laser operating in the continuous (vs. pulsed) mode. The same parameters were used for specimens that were welded only, welded through, and welded through a gap in the adhesive. The goal in parameter selection was to obtain a 5-mm-diameter weld spot or nugget at the interface of the thick-to-thick blanks and a 3-mm-diameter weld spot or nugget at the interface of thin-to-thin and thin-to-thick blanks.[2] Parameters of beam power, beam-on time, and any beam movement (actually, CNC table movement) to increase spot weld size by circle generation were not changed from weld-only to weld-bonded joints because it was assumed spot size would not change much with the different types of samples. Final laser welding parameters are given in Table 4.

Adhesive Bonded-Only Test Specimen Preparation

For all test coupons involving adhesive bonding, whether alone or in combination with subsequent laser spot welding, regions to receive adhesive were left open, while regions not to receive adhesive were covered by masking tape.[3] For weld-bonded specimens in which the spot welds

2. For the thin-to thick combination, laser spot welding was always performed from the thin side to produce the spot weld by a melt-in (or conduction) mode into the thick back piece.

3. The masking tape could be left on single-lap shear specimens until after the adhesive was cured (or until supplemental laser spot welding) as it was outside the overlap area and could be removed. For coach (T-coupon) peel specimens, the masking tape, while not accessible (being fully sandwiched between blanks), could be left in place without affecting test results.

would be made in openings (or gaps) in the adhesive (so as not to have to weld through the adhesive with whatever problems that might cause) an additional (second), transverse strip of masking tape approximately 8.5 mm (3.8 in.) wide was applied to create a small (approximately 8 mm) square or rectangular gap at the coupon overlap midpoint. After masking, adhesive was spread evenly over the unmasked region and 20–50 glass beads measuring 0.25 mm (0.010 in.) in diameter were sprinkled on. These nondeformable beads fixed the bond-line thickness (which is a variable needing to be controlled in adhesive bonding).

Betamate 4601 adhesive, produced by Essex Specialty Products, Inc. (a division of Dow Chemical Co.), is a one-part, high-performance heat-curing (or heat-activated) structural epoxy adhesive (Ref. 13). It was allegedly designed specifically for use on pretreated aluminum and aluminum alloys, and comes as a paste that can be dispensed manually or automatically/robotically. This adhesive is widely used in the automobile industry for structural assembly. Table 5A and B gives the adhesive's cured physical properties and performance properties in joints.

The cure cycle used was 30 minutes at 175°C, with a ramp up from room temperature at no more than 5°C per minute.

Weld-Bonded Test Specimen Preparation

The weld-bonded test specimens were of two types to assess alternative approaches for laser welding through the adhesive or only through gaps within the adhesive. Welding of both specimen types was performed as described above under the heading "Welded-Only Test Specimen Preparation." The adhesive application was performed as described above under the heading "Adhesive Bonded-Only Test Specimen Preparation." The only change was that preliminary weld-bonding trials (involving the development of laser beam spot welding parameters) showed the heat of the laser spot welds caused the uncured adhesive to soften and flow outside masked areas. Welding trials with pre-cured coupons showed no improvement in laser beam/adhesive interaction, so coupons were left in the uncured condition during all welding of test coupons to allow the adhesive to flow back around newly made spot welds (for maximum effect on softening stress concentrations at the spot welds).

Property Testing

All single-lap static tensile shear testing and coach peel testing were performed on an Instron 4204 machine with a 50-kN (11,240-lb) load cell and 1.5-in.-wide (38-mm-wide) wedge grips. Except where noted, testing was performed at room temperature, with the other testing occurring at 100°C (as noted). Three repeat tests were performed for each and every condition of paired-coupon (blank) thicknesses, lubricant or no lubricant, and laser (spot) weld only, adhesive bonding only, and combined weld bonding either welding through the adhesive or into openings (gaps) in the adhesive, with the average value being plotted.
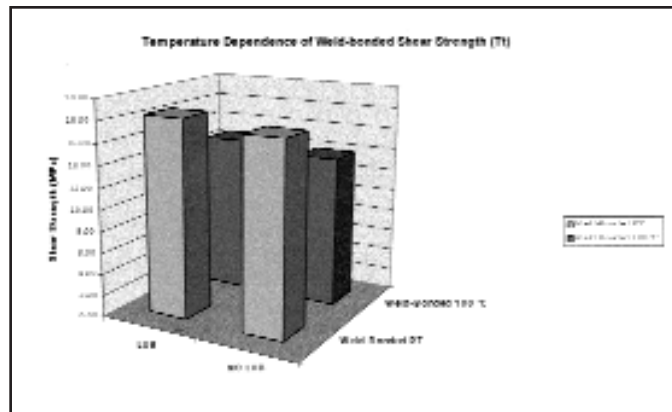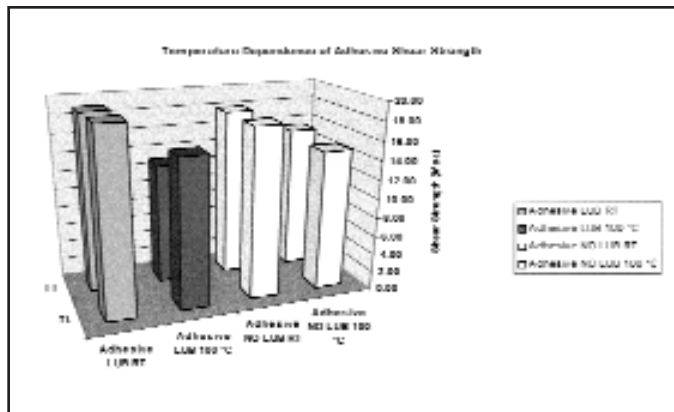
Single-lap tensile shear fatigue testing

Table 3B — Full Test Matrix for the Study; Part B, Static Peel

Sample Type	Orientation	Overlap (mm)	No. at RT	No. at 100 °C	No. Extra	No. Total
Adhesive, lubricant	thick thick	38.1	3	3	1	7
	thin thick	38.1	3	3	1	7
Adhesive, no lubricant	thick thick	38.1	3	3	1	7
	thin thick	38.1	3	3	1	7
Weld, lubricant	thick thick	38.1	3		1	4
	thin thick	38.1	3	3	1	7
	thin thin	38.1	3		1	4
Weld, no lubricant	thick thick	38.1	3		1	4
	thin thick	38.1	3	3	1	7
	thin thin	38.1	3		1	4
Weld, through adhesive lubricant	thick thick	38.1	3		1	4
	thin thick	38.1	3	3	1	7
	thin thin	38.1	3		1	4
Weld, through adhesive, no lubricant	thick thick	38.1	3		1	4
	thin thick	38.1	3	3	1	7
	thin thin	38.1	3		1	4
Weld, gap in adhesive, lubricant	thick thick	38.1	3		1	4
	thin thick	38.1	3	3	1	7
	thin thin	38.1	3		1	4
Weld, gap in adhesive, no lubricant	thick thick	38.1	3		1	4
	thin thick	38.1	3	3	1	7
	thin thin	38.1	3		1	4
					Total	118

No. of thick pieces 132.
No. of thin pieces 104.
All with 4.625 in. to hole.

Table 3C — Full Test Matrix for the Study; Part C, Shear Fatigue

Sample Type	Orientation	Overlap (mm)	No. at RT	No. at 100 °C	No. Extra	No. Total
Adhesive, lubricant	thick thick	15	5		2	7
Adhesive, no lubricant	thick thick	15	5		2	7
Weld, lubricant	thick thick	15	5		2	7
	thin thick	8	5		2	7
	thin thin	8	5		2	7
Weld, no lubricant	thick thick	15	5		2	7
	thin thick	8	5		2	7
	thin thin	8	5		2	7
Weld, through adhesive lubricant	thick thick	15	5		2	7
	thin thick	8	5		2	7
	thin thin	8	5		2	7
Weld, through adhesive, no lubricant	thick thick	15	5		2	7
	thin thick	8	5		2	7
	thin thin	8	5		2	7
Weld, gap in adhesive, lubricant	thick thick	15	5		2	7
	thin thick	8	5		2	7
	thin thin	8	5		2	7
Weld, gap in adhesive, no lubricant	thick thick	15	5		2	7
	thin thick	8	5		2	7
	thin thin	8	5		2	7
					Total	140

No. of thick pieces 154.
    No. with 4.625 in. to hole 112.
No. with 4.4865 in. to hole 42.
No. of thin pieces 126.
    All with 4.4865 in. to hole.

Fig. 7 — Graph showing temperature effect on adhesive-only static shear strength.

Fig. 8 — Graph showing temperature effect on weld-bonded static shear strength.

Table 4 — Final Laser Welding Parameters Used throughout the Study

Thin to thin (weld only)
865 W
0.040 in. R circular travel
Speed: 50 in./min

Thin to thick (weld only and WB)
1200 W
0.040 in. R circular travel
Speed: 50 in./min

Thick to thick (weld only and WB)
1600 W
0.048 in. R circular travel
Speed: 15 in./min

Thin to thin (WB)
1015 W
0.040 in. R circular travel
Speed: 50 in./min

Table 5 — Properties for Betamate 4601 Structural Adhesive

Cured Physical Properties

Nominal Cure (Metal Temperature)	15 minutes @ 175°C (347°F)	
	Modulus	Tensile
Young's Modulus, @ 23°C	2.69 GPa	56 MPa
Tensile Stength @ -40°C	3.15 GPa	76 MPa
@ 80°C	1.73 GPa	20 MPa
Elongation at break (23°C),		8.9%
Elongation at break (-40°C)		7.0%

Performance Properties

Test Substrate	2-mm-thick Alcan 5754 alloy aluminum, PT2 pretreatment	
Bondline Thickness	0.254 mm (0.010 in.)	
Lap Shear 23°C	23.3 MPa (3380 psi)	
-40°C	23.7 MPa	
82°C	23.8 MPa	
Peel Strength @ 23° C N/m (pli)		13130 (75)
@ -40°C		12700 (72)
ISO 11343	Dynamic Resistance to Cleavage @ 3 m/s	
23°C	700 Newtons	
-40°C	220 Newtons	

was performed initially at Rensselaer Polytechnic Institute (RPI), but then predominantly at Winona State University (WSU) using an Instron Model 1331 Load Frame with Instron Series 8500 Controller, with 1-in. Instron Hydraulic Wedge Grips (with a 21-MPa gripping pressure), and a 50-kip (about 250-kN) load cell at RPI and a 10-kip (about 50-kN) load cell at WSU operating at 20–22 Hz.

In all cases, five to seven specimens (of each joint condition) were run at various stress levels to develop a stress vs. number of cycles (S-N) graph for each condition. (Later on, results were plotted as maximum load vs. number of cycles due to inherent difficulties of calculating stress, as will be described below.) One million (10^6) cycles was set as the maximum life level for the tests to determine fatigue strength (or fatigue limit). The specimens were run with a fully reversing ($R = -1.0$) sinusoidal waveform at a frequency of 20–22 Hz. All testing was performed at room temperature under normal atmosphere.

Results and Discussion

Single-Lap Tensile Shear Test Results

For the adhesive bonded-only tests, there was an insignificant difference between lubricant and no-lubricant results (Fig. 3), confirming that the Betamate 4601 adhesive was, indeed, designed to work with the dry lubricant. For weld-only tests, the no-lubricant specimens exhibited higher shear strengths than lubricant specimens (Fig. 4), indicating that the dry lubricant has adverse effects on the laser spot welds, even if not on the beam-metal interaction. Weld-bonded tests exhibited an insignificant difference between lubricant and no-lubricant specimens (Fig. 5); suggesting any possible adverse effect of lubricant is overshadowed by the general adverse effect of the adhesive itself on the quality of the laser spot weld due to violent outgassing, molten metal expulsion (leading to hollow spot welds), and charring due to the laser's interaction with the polymeric adhesive.

Joint thickness had no noticeable effect on adhesive-only samples, but did have an effect on weld-only and weld-bonded samples (Figs. 3–5). These results are consistent with the fact the load-carrying ability of an adhesive bonded joint is dependent on the amount of surface area bonded and the inherent strength of the adhesive, with material (i.e., adherend) thickness having a secondary effect, at least as long as thickness differences do not result in significant degrees of joint rotation under eccentric loads in single-lap specimens (Ref. 8). However, the thickness of joint elements does have an effect on a welding process, including laser beam spot welding. The thick-to-thick combination posed the greatest problem for laser spot welding, requiring more beam energy to melt through the 2-mm-thick aluminum alloy sheet on the beam entry side with less penetration into the backing sheet, resulting in inferior weld strength. (This could be overcome by refining welding parameters for this thickness combination.) With the thin-to-thick and thin-to-thin combinations, the laser beam only had to penetrate a 1-mm-thick sheet of aluminum alloy on the entry side (in each case) to produce greater penetration into the backing sheet and a stronger weld. Between these two, the thin-to-thick combination (actually the most common joint found in vehicles) exhibited the superior strength, possibly attributable to the thicker backing sheet providing a larger heat sink and less thermal damage to the adhesive.
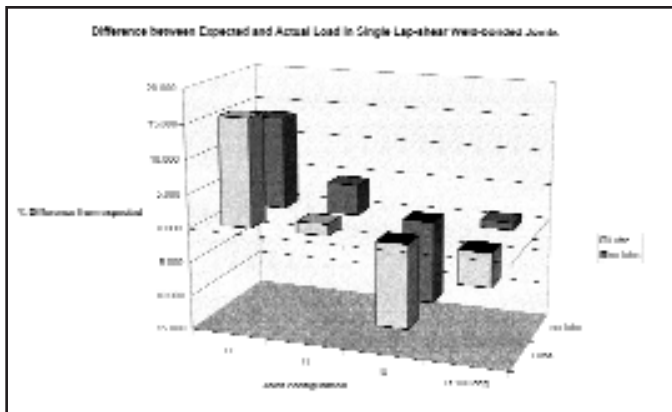
Fig. 9 — Plot showing the synergistic effect of weld-bonding on static shear strength compared to the simple addition of weld-only and adhesive-only results.
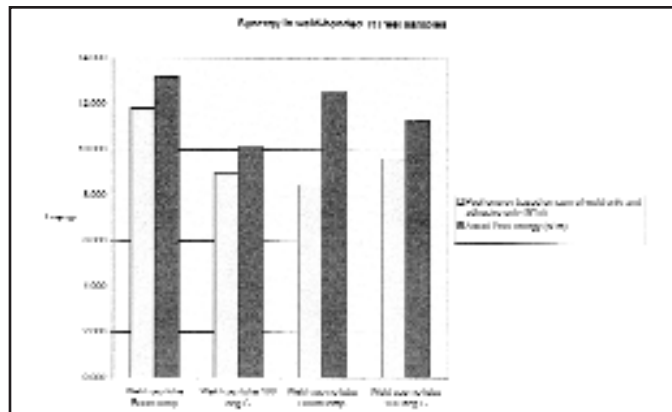

Fig. 10 — Plot showing the synergistic effect of weld-bonding on energy absorption in coach peel tests compared to the simple addition of weld-only and adhesive-only results.
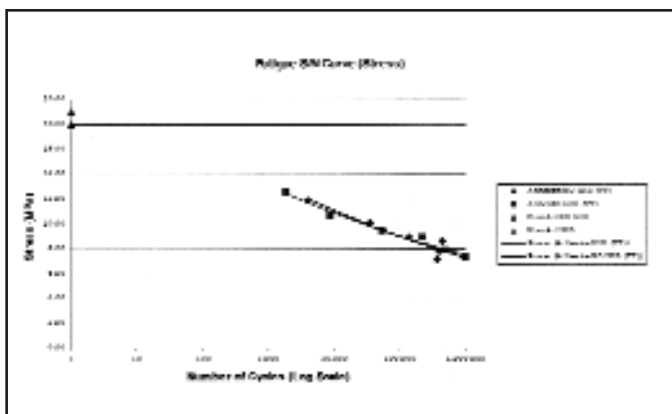

Fig. 11 — Plot of the fatigue S-N curves for bonded-only samples without ("no lubricant") and with ("lubricant") dry lubricant present showing no difference in behavior.
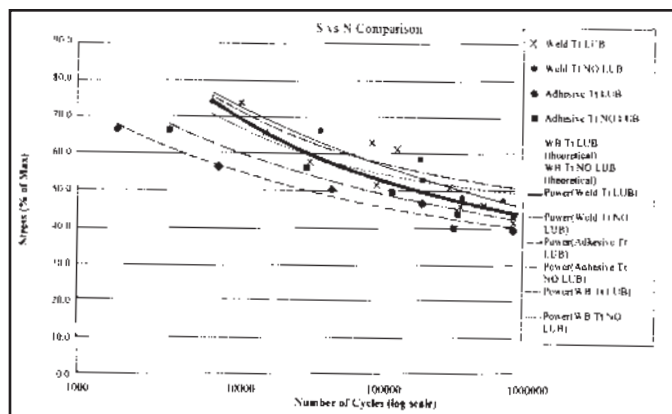

Fig. 12 — Plot of fatigue testing results for welded-only, bonded-only, and weld-bonded samples of different thickness and lubricant conditions.

Testing temperature had no effect on the weld-only results (Fig. 6), as would be expected for such a low temperature (100°C) for an alloy with a melting point near 600°C. However, joint static shear strength was adversely affected in both the adhesive-only (Fig. 7) and weld-bonded (Fig. 8) tests by even modestly elevated temperatures (i.e., 100°C). This is, without question, the direct result of the polymeric adhesive softening upon heating (as do most viscoelastic materials), thereby having a reduced ability to carry (shear) loads.

The weld-bonding data are quite interesting. Static shear stress data for weld-bonded specimens were considered two ways: 1) a stress was calculated (in the conventional manner) by dividing the peak load (sustained) by the combined areas of the adhesive as well as of the weld, while 2) an "expected load" was also determined by multiplying the area of adhesive bond by the measured value of shear strength (stress) for the adhesive only and adding the product of the area of the spot weld

and the measured value of shear strength (stress) for the weld only. The stress used to determine what level of load could be carried came directly from the average stress from an adhesive-only and a weld-only test of the same joint geometry (due to differences in stress based on joint geometry). The expected load was then compared to the actual load as a percentage of the difference between the two values divided by the expected load. It reads: the actual load is *x* percentage higher than what was expected, if *x* is positive, and the actual load is *x* percentage lower than what was expected, if *x* is negative. By this technique there appears to be a positive (synergistic) effect in the thick-to-thick, a marginally positive (synergistic) effect in the thin-to-thick, and a negative (degradation) effect in the thin-to-thin joints. One reason for the apparent degradation in the thin-to-thin joints could be due to differences in the shear strengths (stresses) of adhesive-only joints that are thin-to-thin vs. thin-to-thick. Only further

testing will resolve this question. This effect is shown in Fig. 9.

Coach (T-Coupon) Peel Results

The customary way to measure the peel strength of an adhesive is by using the average peel force. It is common to measure the strength of welds (especially, spot welds) by looking at the maximum force. It was determined in this study that in order to see if there is, in fact, any synergistic benefit of combined weld bonding, bond energy would have been used. The two main reasons for this were 1) the spot welds break 19 mm (0.75 in.) after the adhesive starts peeling (due to the way the coupon peels) and 2) high peel forces can exist for very short periods of time and actually absorb less energy than if a lower peeling force were required to be applied but for a much longer time. In other words, it is the area under force-displacement curves for weld-bonded specimens that is important in energy absorption. If
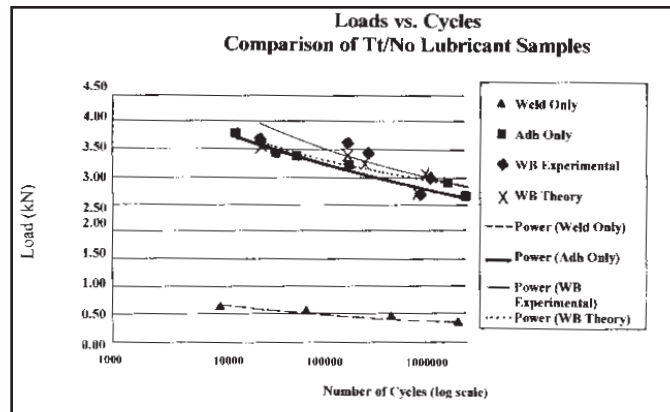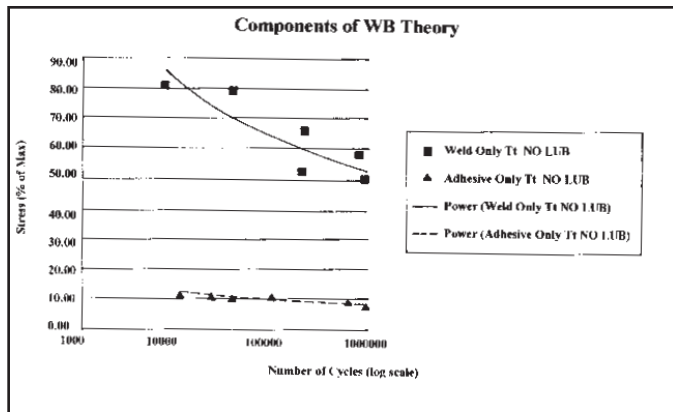
Fig. 13 — Fatigue S-N plots for adhesive bonded-only and laser beam spot-welded-only samples, along with computer-generated regression lines.

Fig. 14 — Comparison of "theoretical" and "experimental" P-N curves for weld-bonded samples, with the component curves for welded-only and bonded-only also given.

there is a synergistic effect of weld-bonding, the area under the force-displacement curve for a weld-bonded specimen should be greater than the sum of the areas for a weld-only and an adhesive-only curve, correcting for the areas of each in the weld-bonded specimen.

When comparing the energies for the thin-to-thick specimens, it is evident there is a synergistic effect of weld bonding, averaging about 23% higher than expected by simple additive effects. This is shown in Fig. 10.

Single-Lap Tensile Shear Fatigue Test Results

Six specimens each of lubricant and no-lubricant thick-to-thick adhesive bonded-only samples were tested at RPI to establish a uniform testing procedure and to determine broad life-vs.-load behavior. The starting fatigue load level was taken as approximately 50% of the maximum static load required to cause static tensile fracture. This load level resulted in a fatigue life of approximately 100,000 cycles for both conditions. From this "base point," higher and lower loads (as a percentage of the maximum static load to cause fracture) were applied in order to generate a stress vs. number of loading cycles to failure (S-N) curve. At approximately 65% of the maximum static fracture load, fatigue specimens survived only 1000–4000 loading cycles. This was taken as the maximum load level for fatigue testing, as any load above this would have resulted in life of very little interest. A fatigue life of 500,000 cycles was obtained with load levels between 40 and 45%. The sought-after 1,000,000 (10^6) cycle maximum life (or fatigue limit) was predetermined from regression analysis to occur at a load level of 38–40% and, in fact, this load level did result in 10^6 cycles life.

Figure 11 shows there is virtually no difference in the fatigue behavior of lubricant and no-lubricant specimens for adhesive bonded only, thick-to-thick condition. Within expected error from various sources, the regression lines lie on top of one another.

Using this same general testing procedure, all remaining fatigue testing was performed at Winona State University using the system described previously under the heading "Property Testing."

First, thin-to-thick and then thin-to-thin combinations of adhesive bonded-only samples were tested. Again, no effect (positive or negative) of dry lubricant was found, although there was an effect of adherend (or joint element) thicknesses. Thin-to-thick samples showed an upward shift of the S-N curve compared to thick-to-thick samples, and thin-to-thin samples showed an upward shift even to the thin-to-thick S-N curve. No particular explanation can be given for this behavior except that fatigue is a surface-related phenomenon, and the relative surface area (to volume ratio) is greater for thin-to-thick than thick-to-thick, and greatest of all for thin-to-thin joint combinations.

Results of fatigue testing of weld-only specimens showed lower life at a stress level, or, alternatively, a lower tolerable stress for any particular required life — Fig. 12. This result is expected, given that applied shear stress tends to concentrate discrete (spot) welds, thereby lowering resistance to fatigue near such welds.

The last samples to be tested were the weld-bonded samples in which laser spot welds were made at points where there was an intentional gap in the preapplied adhesive. Gaps were necessary since the laser beam interacted violently with the polymeric adhesive, causing severe outgassing of volatiles, and due to inherent thermal decomposition of the polymer it-

self, with attendant expulsion of molten aluminum from newly formed molten spots, large voids and carbonaceous residue from pyrolysis were left. Both thin-to-thick and thin-to-thin joint combinations were tested, with no real effect from the dry lubricant. The possible synergistic effect of weld bonding on fatigue life is more difficult to determine.

The difficulty of trying to determine whether there is any synergistic benefit of combining (laser) spot welding and adhesive bonding is trying to account for the individual effect of each joining process alone and then seeing if the weld-bonding combination results in more than an additive effect. If only one particular joining process is being considered, it is obvious that doubling the number of spot welds (or, actually, total spot weld area) would greatly increase the fatigue life by halving the stress in each weld. Likewise, if the area of adhesive bonding is doubled, the stress in the adhesive is halved, and the fatigue life is increased considerably. However, when spot welds and adhesive are combined, it is more difficult to determine what the stress is in each, as they are different since the inherent stiffness (as measured by modulus of elasticity) is so different for the metal spot welds and polymeric adhesive.

In an attempt to compare actual results to see if there is greater than an additive effect (of spots plus adhesive), a "theoretical" S-N curve for the weld-bonded data was calculated and then compared to the experimentally determined S-N curve. Only results for no-lubricant thin-to-thick samples were analyzed because lubricant had an adverse effect on spot welding and because the thin-to-thick point combination is the most popular in automobile structure assembly.

Fatigue S-N curves were plotted for adhesive bonded only and spot welded only

joints, as can be seen in Fig. 13. A trend regression line was computed for each of these test conditions data sets and the equations for these lines were used to calculate theoretical load components for the weld-bonded samples. The components (for adhesive only and weld only) were added together and then plotted as load vs. number of cycles of life to give a P-N curve. The experimental and theoretical P-N curves, along with the component curves, are shown in Fig. 14. It can be seen that the experimental P-N curve starts out above the theoretical curve, suggesting some synergistic effect, but then appears to simply overlie (overlap) the theoretical curve area 600,000 cycles of life. This seems to indicate weld-bonded specimens (joints) equal or exceed the theoretically predicted, purely additive effects of adhesive bonding and spot welding alone.

Conclusions and Future Directions

Laser beam weld bonding offers improvements in in-plane static tensile shear strength, out-of-plane coach peel strength (and, especially, energy absorption), and fatigue performance (i.e., strength at any required life to 10^6 cycles) that appear to be the result of a synergistic effect between the two processes in combination. Problems encountered when the laser beam interacts with the polymeric adhesive that degrade the quality of the spot weld in the aluminum alloy need to be overcome to realize full potential of the hybrid process of weld bonding. Further testing is required in coach peel and fatigue to conclusively demonstrate any synergistic benefit of combined spot welding and adhesive bonding.

Future work will address several ways of practicing laser beam spot welding in a way in which the beam will 1) not have to interact with the temperature-sensitive, volatile polymeric adhesive and 2) assure that the adhesive back-fills around newly made spot welds to maximize stress concentration "softening" effects.

References

1. Aluminum Applications for the Automobile Industry, Nov. 2001,

2. Warren, A. S., Wheatly, J. E., Marwick, W. F., and Meadows, D. J. 1989. The building and test-track evaluation of an aluminum structured Bertone X1/9 vehicle, SAE Paper 890718.

3. Messler, R. W., Jr., 1999. *Principles of Welding: Processes, Physics, Chemistry & Metallurgy*, New York, N.Y.: John Wiley & Sons, Inc., pp. 237–244.

4. *Welding Handbook*, 8th Edition, Vol. 3, Part 1, Materials and Applications, 1996. Ed. W. R. Oates. Miami, Fla.: American Welding Society, pp. 72–79.

5. Private Communications: R. W Messler, Jr., and D. R. Sigler, Welding Engineer, GM R&D Center, General Motors Corp., Warren, Mich. October 1, 2002.

6. *Welding Handbook*, 7th Edition, Vol. 4, 1982. Ed. W. H. Kearns. Miami, Fla.: American Welding Society. pp. 316–387

7. Schwensfeir, R. J., Jr., Trenkler, G., Delagi, R. G., and Forster, J. A. Comparison of bond in roll-bonded and adhesively bonded aluminums. *Joining Technologies for the 1990s* by J. D. Buckley and B. A. Stein, 1986, Noyes Data Corp., pp. 322–238.

8. Messler, R. W., Jr., 1993. *Joining of Advanced Materials*. Stoneham, Mass.: Butterworth-Hennemann, pp. 16–26.

9. Parmley, R. O., 1989. *Standard Handbook of Fastening and Joining*. New York, N.Y.: McGraw-Hill, Inc. pp. 12-1–12-12.

10. Landrock, A. H., 1985. *Adhesives Technology Handbook*. Park Ridge, N.J.: Noyes Publications. pp. 190–191 and 64.

11. *Welding Handbook*, 8th Edition, Vol. 2, Welding Processes, 1991. Ed. R. L. O'Brien, Miami, Fla.: American Welding Society. pp. 550–552.

12. Messler, R. W., Jr., 2002. Weld-bonding: the best or worst of two processes?, *Industrial Robots,* 29(2): 1–11.

13. Betamate 4601 Product Sheet, Essex Specialty Products, Inc. (Ref. undated).