DESIGNING MATERIALS JOINING FOR LIGHTWEIGHTING

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Abstract

Consumer, industrial, and government products contain many different materials to decrease weight, increase efficacy, and present new functionalities. These include health monitoring devices; consumer goods; electric vertical take-off and landing aircraft (eVTOLs), drones, and aircraft for aerospace; and electric, hybrid, or gas vehicles for automotive. Dissimilar material joints, or mixed-material composites, can be difficult to separate at the end of the products' lives. A profound understanding of the molecular structure at interfaces is required for joints to ensure the product will last its intended life and be detachable. During this presentation, lightweight, strong, and reliable joint designs will be described for both joining and end-of-life separation. One example is polymer-to-metal direct joining where heat is used for the joint assembly and disassembly so that the polymer and metal can be sorted into different recovered streams for reuse.

Introduction and Motivation

As products get smaller and more functional, they require increasingly specialized materials to be used adjacent to one another. The varied materials that make up items in everyday use, like phones, smartwatches, and cars, need to be joined together using efficient new processes. One such process — enhanced polymer-to-metal joining — has become progressively more important in the manufacture of everyday items. This type of joining enables a strong joint without the need for adhesives or fasteners, reducing the number of consumables needed during the manufacturing process. It also creates a dissimilar joint that can be separated at end of life so that the materials can be recycled with their proper streams.

Review of Related Work

Polymer-to-metal joining without out adhesives or fasteners has been studied by researchers over the past two decades. Nine methods for such a joining process are reviewed herein.

1. Laser-assisted metal to plastic (LAMP) direct joining process showed that penetration, or keyhole, welding can be accomplished by heating the materials interface with a laser, melting the polymer (and in some cases the metal), and growing an oxide layer on the metal for bonding after cooling.[1] Sometimes bubbles occur at the interface which decrease strength. It has short cycle times, no additional components, and small polymer deformation.
2. Ultrasonic torsion welding uses constant force applied to the top workpiece.[2] A sonotrode oscillates torsionally to create heat. The heat is conducted to the joint to melt the plastic. This is highly reproducible with short processing times and low energy input.
3. Spot welding uses a constant force to push two electrodes onto the top work piece.[3] In this joining, a current of 5 kA is applied for 250-500 milliseconds, which resistively heats the metal and melts the plastic. The parts remain under force until cooled. It requires short cycles times and yields limited plastic degradation with low equipment costs.
4. The clinching, or press-joining, sheet forming process requires a punch be used to plastically form an interlock.[4] The processing parameters include joining force, groove size, die depth, punch diameter, and temperature. It requires a large deformation of the parts but can be accomplished quickly.
5. Friction press joining induces heat by friction and pressure causing the thermoplastic melt to adhere to the metal.[5] Process parameters include rotational speed, feed rate, and z-axis force. Surface treatments have been shown to increase the strength of the joint because it is dependent on surface area and Van der Waals forces. It requires little deformation of the parts to make the joint.
6. Friction spot welding requires a static clamping ring and sleeve and pin that can independently rotate to create heat from friction, thus heating the metal and melting the polymer allowing mechanical interlocking and

adhesion.[6] The process parameters include tool rotational speed, joining time, plunge depth, and normal force. It is a low-cost joining method with small part deformation.

7. Friction stir welding uses a rotating pin to displace material at a butt joint interface and create a solid-state weld.[7] Process parameters include pin diameter, linear velocity, and rotational speed. Soft metals, like aluminum, and high molecular weight polymers, like high density polyethylene (HDPE), have shown joints with high strength. The primary joining mechanism is mechanical interlocking, with Van de Waals forces being the secondary method. No surface treatments are needed, and it can be applied to large parts.
8. Cold spray is a technique in which a metal powder is heated and sprayed at a surface where it adheres primarily by mechanical interlocking.[8] The goal is to get good adhesion without polymer erosion. Process parameters include powder type, size, velocity, temperature, feed rate, gas type, substrate temperature, and spray distance. There are many tunable parameters, and it can be automated using robotics, but only applies a thin layer of metal to the polymer surface.
9. Injection overmolding can be used to join polymer to metal when a metal insert is placed in the injection molding tool, molten polymer is flowed around the part, then allowed to cool and solidify.[9] Adhesion forces can be increased by surface treatments, like plasma, on the metal insert. Process parameters include polymer melt temperature, mold/metal insert temperature, hold time, and pressure. It can be used on large surface area parts or small encapsulated parts, and it is highly repeatable.

Each of these joining options has benefits and drawbacks depending on the materials, design, and functional requirements of the products being manufactured. Many of these joints could also be disassembled at the end-of-life using heat because they all include a thermoplastic. The following sections include details for a novel polymer-to-metal joining process that yields high joint strengths.

Technology Approach

Enhanced polymer-to-metal joining is a two-step process. The first process is laser etching the surface of the metal. EWI has optimized this process to melt microscale valleys with overhanging fingers or bridges on various grades of aluminum (Figure 1), stainless steel, and titanium. The melt is pushed up the wall of the valley, creating a protrusion with ends that overhang the valley. This enables the polymer to form a stronger bond as the surface is clean and has a mechanically functional topography. For etching, EWI uses a Laser Marking Technologies 100W 1064-nm pulsed fiber laser.

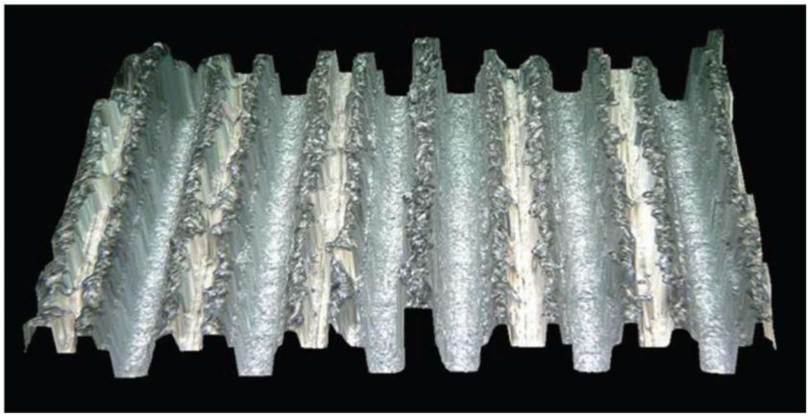

Figure 1. Confocal scan of valleys (~60 µm feature depth) with overhanging fingers or bridges on etched aluminum

The second process for joining is to melt the polymer into the etched metal surface. EWI has shown feasibility on the following polymers: polyamide/nylon 6 (PA6/N6), polyethylene terephthalate (PET), polystyrene (PS), HDPE, polyvinyl chloride (PVC), and polypropylene (PP). Other thermoplastics and uncured thermosets will also form a strong joint. Polar polymers create a higher strength joint due to the carbon-oxygen-metal type of covalent bonding that occurs.[10]

Enhanced polymer-to-metal joining requires both force and heat, which cause material to flow into the microfeatures. EWI's engineers have used different methods for heating with similar results. Two of the methods are transmission laser heater using a 1-μm wavelength continuous laser, and induction coil, which heats the metal and thus also the polymer at the interface, as shown in Figure 2.

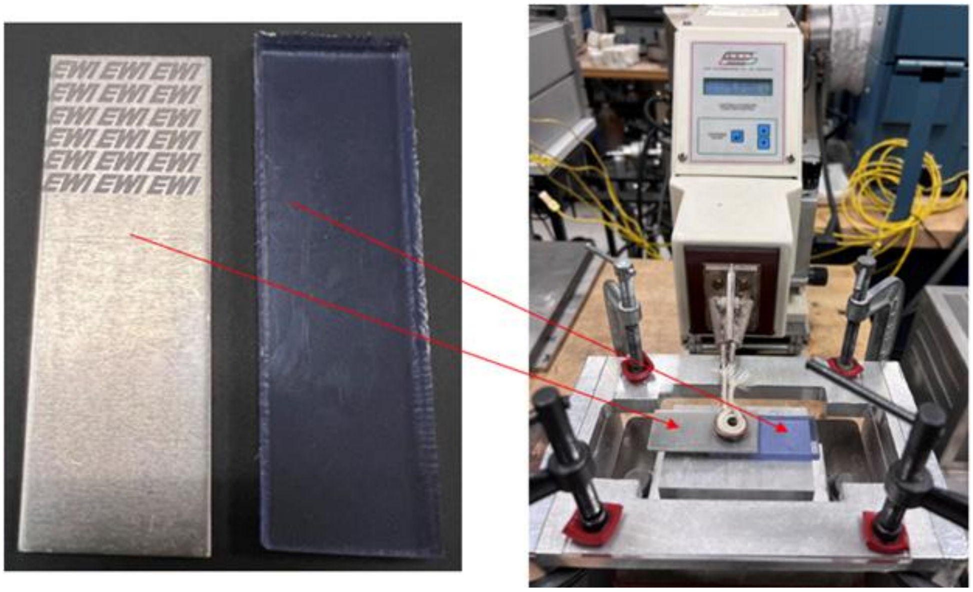

Figure 2. Etched aluminum and PVC lap shear specimen (left); induction coil heating the specimen while force is applied to join the materials (right)

The specimen after joining is shown in Figure 3. Very little welding flash is created during the process because once the microfeatures are filled, the flow is stopped by cooling the polymer. Also in the same figure, a similar part has been disassembled using heat. This makes it simple to sort the materials into their respective streams for recycling and reuse.

Figure 3. (left) PVC to aluminum-joined lap shear specimen (right) heated and disassembled

Figure 4 shows a mocked-up battery box with 19 battery cells (18650 type) connected by stainless steel busbars that were parallel gap welded to the terminals. The top edge of the aluminum box was laser etched, and the translucent polymer was attached through heat and force. This process can be scaled-up to structures for electric vehicles.

Figure 4. PVC top-to-aluminum battery enclosure

Cross-sections of the joint were inspected with microscopy, shown in Figure 5. In this case, PET (white, right) was heated and pushed into etched aluminum microfeatures (black, right). This cross-section shows full integration of the polymer reaching the bottom of the microfeatures. Joining parameters that are between the polymer's critical flow temperature and degradation must be used to ensure this full integration occurs without damaging the polymer. It is best to measure the thermal properties of the polymer using a differential scanning calorimeter (DSC) and thermogravimetric analyzer (TGA) to determine the optimal joining conditions before attempting the joining process.

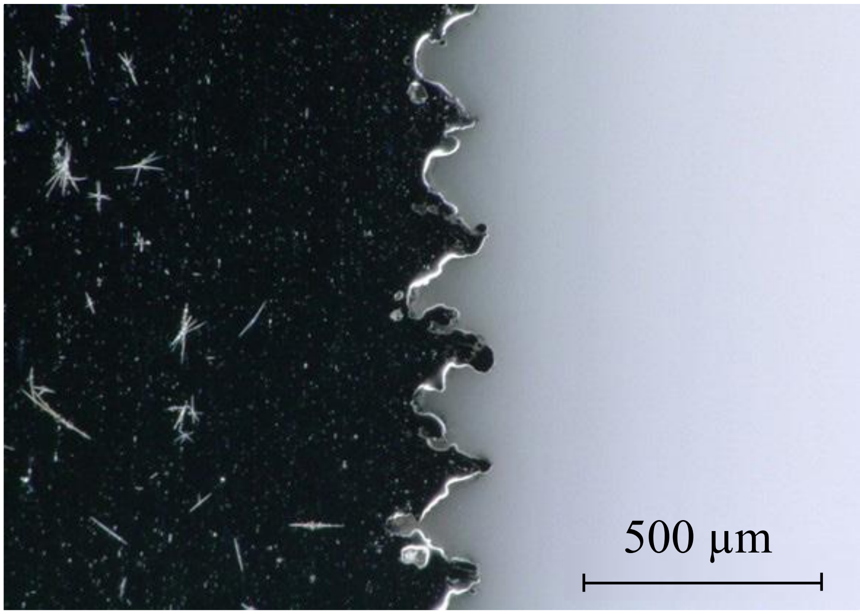

Figure 5. Cross-section of a polymer (right, white) to aluminum (left, black) joint showing full flow of polymer into aluminum microfeatures

Lap shear specimens were pulled to failure to test their strength using a universal test stand. Some reached as high as 2000 lbf for a 1-in.^{2} bonded area. Many of the specimens failed in the bulk polymer, not at the joint, showing the joint was stronger than the bulk polymer for a shear configuration.

To ensure that tested samples broke at the joint instead of in the polymer bulk, butt joints were made (Figure 6). The etched and joined area in this example was 0.25×1.00 in. As shown in Figure 7, these specimens demonstrated strength up to 1069 lbf (29 MPa). Furthermore, EWI developed an enhanced surface modifying technology that can increase the surface area of covalent bonds at the interface between polar polymers (PA6, PET) and the metal by 30%, pushing their strength up to 1374 lbf (38 MPa). If high strength is not required, or if a certain break strength is desired, it can be tailored by changing the depth of the microfeatures.

Figure 6. Butt joint of PET to aluminum

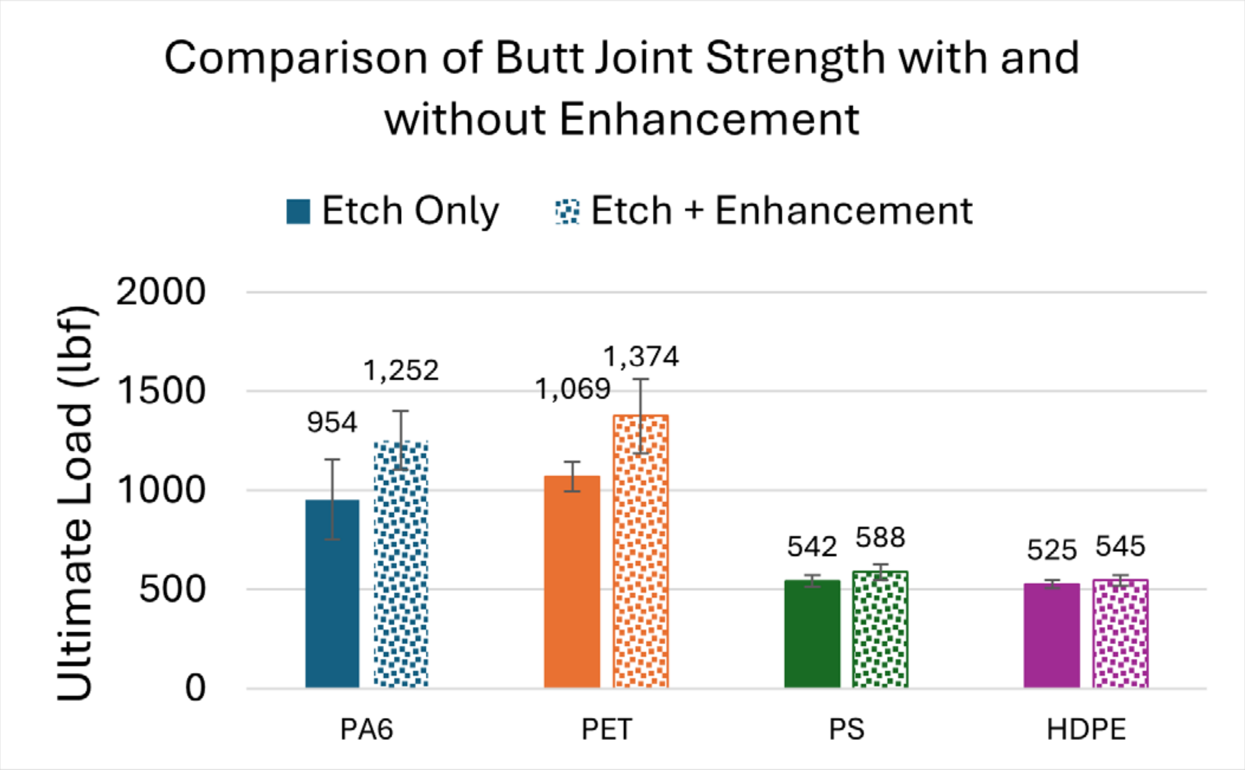

Figure 7. Butt joint strengths (0.25 in.^{2} area)

Durability testing has shown that these joints can be thermally cycled between 0 and 65°C without a change in their strength. The joints have also been disassembled and rejoined, showing that products that are made with this technology can be serviced. EWI has also designed microfeatures that yield hermetic joints like the demonstrator part holding liquid displayed in Figure 8. Other parts have been tested by air leak decay to show gas hermiticity.

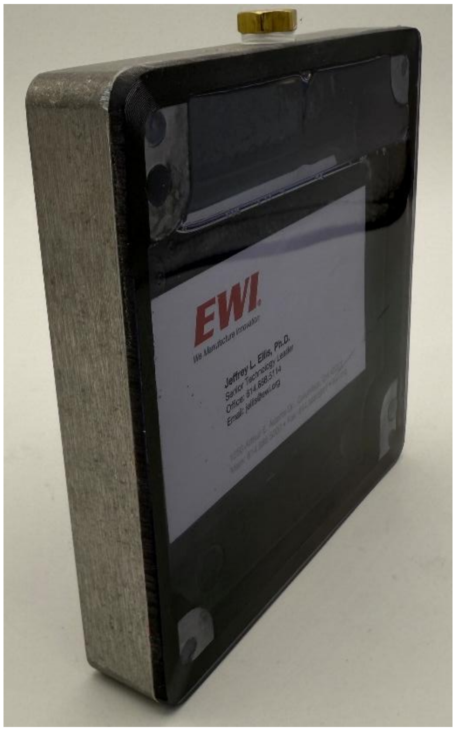

Figure 8. PVC-to-aluminum joint container holding liquid to demonstrate a hermetic seal

Discussion

As shown in this paper, there are multiple ways to join polymers to metals without adhesives or fasteners. These technologies can be the backbone of lightweight, multifunctional products and vehicles of the future. These strong, repeatable, reliable joints may be easy to separate back into their components for sorting to recycle and reuse. As large products adopt these joining processes, new manufacturing techniques will need to be implemented into production lines.

Conclusions and Recommendations

The need for the joining of more dissimilar materials continues to increase as it makes products lighter, smaller, and more functional. More materials mean more difficulty in recycling or reusing them at the end of product life. EWI has demonstrated polymer-to-metal joining for butt and shear joint geometries. The strengths of these joints have reached an average of 1374 psi (38 MPa) for a butt joint and higher for shear joints. Furthermore, liquid and gas hermeticity has been demonstrated. This new joining technique can eliminate adhesives and fasteners from structures make them lighter weight. Finally, disassembly using heat at the joint for servicing or end-of-life separation is theoretically possible for larger structures. Designs on consumer products may be more complicated and larger than the coupons demonstrated bringing new challenges to assembly and disassembly. To meet real product demands, rotating fixtures, programmable robot arms, and post-etching forming processes are feasible solutions that can be explored.

Acknowledgements

EWI developed this technology on an internal research and development project and purchased all materials.

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About the Author

Dr. Jeff Ellis is a Senior Technology Leader at EWI. He is responsible for steering the polymers technology roadmap, developing strategies for external engagements, innovating new plastics technologies, and ensuring high technical quality of proposals and reports for customer projects.