A Competitive Advantage Through Innovation

G C McGrath, I A Jones, P A Hilton E J C Kellar, A Taylor
TWI

R Sallavanti
Gentex

Copyright © 2001 Society of Automotive Engineers, Inc.

ABSTRACT

The vast majority of products contain joints, therefore, joining technology is key to the strategic implementation of new materials. This paper considers three innovative solutions to industrial problems.

ClearWeld™

A recently developed technique for laser welding materials, creating a joint almost invisible to the human eye.

AdhFAST™

This novel, three-in-one fastener, allows adhesive to be injected through the middle of the device whilst retaining the joint and controlling bondline thickness.

Vitresyn™

Transparent plastics such as polycarbonate and acrylic have the potential to replace glass in a number of applications, car headlamps and spectacle lenses for example. However, these plastics are relatively soft materials and need protection against abrasion and scuff damage. This recently developed system gives good protection at acceptable cost.

INTRODUCTION

The vast majority of products contain joints, therefore joining technology has three main economic impacts:

- Improved or new technology to allow the production of existing products at reduced cost or better quality.
- Greater freedom in material selection to design and manufacture new products.
- Avoidance of product defects, failures and savings associated with consequential losses.

By managing innovation, TWI has developed a range of processes that can reduce time to market while improving the functionality of components. This paper will focus on three of these processes:

ClearWeld™

AdhFAST™

Vitresyn™

CLEARWELD™

TWI and Gentex Corporation have developed a technique for laser welding plastics with infrared dye, creating a joint almost invisible to the human eye. Typically carbon black would be used as the absorbing medium for the laser light, however, this new approach enables two similar clear (or coloured) plastics to be joined with a minimal mark weld line. The selection of dyes is discussed in terms of strength of light absorption at 1064nm wavelength (Nd:YAG laser), as well as at 808nm and 940nm (wavelengths available from the relatively new diode lasers).

BACKGROUND - The development of the laser as an industrial heat source has resulted in a range of applications that utilise the precise, controllable energy it delivers. Cutting and drilling of a range of metallic and non-metallic materials, and welding of metals (in particular Fe, Ni and Ti based alloys) have become established industrial processes. Lasers have also had an impact on the processing of polymers, with applications being developed initially in cutting and drilling. Early developments in welding plastics with lasers showed that thin films could be joined. However, at this stage in the 1960s and 1970s, CO₂ lasers were the principle power source. The nature of the interaction between the 10.6µm beam from the CO₂ laser and thermoplastic materials, meant an analogue to the deep penetration process used to weld metals could not be developed. The CO₂ laser beam is absorbed at the surface of the plastic, relying on conduction to heat through the thickness of the material, which results in decomposition, vaporisation and charring, before any significant depth of material is melted. However, thin
polyolefin films, of the order 0.1mm thick, have been successfully welded with a CO2 laser at speeds up to 500m/min.\(^2\)

The increasing use of Nd:YAG solid state lasers, and the advent of diode lasers (both producing beams with a near infrared wavelength), meant lasers became available that had a different beam/material interaction with thermoplastics, from that of the far infrared CO2 laser. The laser beam passes through the top (transmitting) layer and is absorbed by the filler in the lower layer, producing sufficient heat to make a weld at the interface between the two parts. This process was first described for welding automotive components in 1985.\(^3\) An example of the transmission welding technique, utilising a visually transmissive plastic material for the upper section and a carbon black loaded plastic for the lower layer, can be seen in Figure 1.

\[\text{Figure 1} \quad \text{Laser transmission weld in 4mm thick polypropylene using a 100W Nd:YAG laser at a speed of 1.6m/min. The weld is at the interface between the light and dark materials}\]

Although infrared absorbing pigments are available which offer distinct stability advantages over infrared dyes, their drawbacks are considerable.

An extension of the transmission laser welding process which allows completely clear or similarly coloured components to be welded by using a dye, clear in the visible range of the spectrum, but tailored to absorb heavily the specific wavelength of the laser beam being used, has also been described.\(^4\)

The nature of the dye means the laser wavelength is absorbed with high efficiency, thus requiring relatively small amounts of the dye at the interface between the two components to be welded. Development work on the process was mainly carried out using polymethylmethacrylate (PMMA) test specimens, and an example of an overlap weld made by applying a painted layer of dye to the joint region between two transparent sheets of 3mm thick PMMA can be seen in Figure 2.

\[\text{Figure 2} \quad \text{Transmission laser overlap weld in clear PMMA made with infrared dye impregnated film at the interface}\]

Although the example in Figure 2 is shown with two visibly clear sheets of PMMA, a dye applied in this way can be used to join several other materials, coloured or otherwise.

**LIGHT ABSORPTION AND ENERGY CONVERSION IN ORGANIC DYES** - Conventional dyes, by definition, absorb visible electromagnetic radiation (380-750nm), the process involving excitation of an electron from the highest occupied molecular orbital of the chromophore into the first vacant antibonding orbital. The process occurs without electron spin change and the dye is promoted from the singlet ground state to the first excited singlet state. This phenomenon has been used extensively in heat mode optical data recording, where a finely focussed laser beam is absorbed by a dye and the heating effect produces a change in the polymer substrate, by melting or ablation. It has been shown, for example, that writing energies as low as 0.1 nanojoule per square micron can produce local temperatures up to ca, 300°C, sufficient to melt most plastics and dyes, if a dye layer absorbing some 99% of the incident energy is employed.\(^5\)

For maximum conversion of light energy to thermal energy by a dye, the dye should absorb as much of the light as possible, and, if broad band radiation is employed, then the naturally broad bands of most dyes are an advantage. However, if laser sources are employed, it is important to match the \(\lambda_{\text{max}}\) of the dye (the wavelength at which maximum absorption occurs) as closely as possible to the laser wavelength. In addition, a narrow band dye is likely to have a much higher molar absorption coefficient at its \(\lambda_{\text{max}}\) than a structurally similar dye with a broad absorption band, and consequently less dye will be needed to achieve maximum absorption of the incident light.

METHODS OF INTRODUCING DYES FOR LASER WELDING OF POLYMER FABRIC MATERIALS - When the incident laser light is absorbed, the dye molecules dissipate the absorbed energy principally as heat to the dye molecules and their local environment.
Dye concentrations of approximately 0.02% on a film weight basis are typically adequate but are a function of the particular dye used as well as the plastics being welded. If the dye is introduced into the bulk of the polymer fabric, clearly this has the advantage that any area subject to the incident laser light will be affected, however the cost of applying dye to the whole fabric could be economically non-viable in some applications.

DESCRIPTION OF THE LASER WELDING PROCESS - The dye at the interface between the materials acts as the site where the light from the laser is absorbed and converted into heat in a well defined area. The area of heating and hence joining, may be defined by either the size of the laser beam or the extent of the dye containing region. In the experiments reported here, both Nd:YAG and diode laser light have been used. Both these laser wavelengths are easily transmitted via optical fibres, which enhances the flexibility of the process in industrial terms.

Nd:YAG lasers are usually employed in a de-focus position to produce a spot of laser energy some few mm in diameter. This energy profile is almost ideal for the fabric welding process. The welding occurs as the heat generated in the dye is sufficient to melt of the order \( \approx 0.1\text{mm} \) of the polymer fabric . The heat generation at the interface is controlled by the absorption coefficient of the dye layer and the processing parameters. The main parameters, for a given width of weld, are laser power, energy distribution in the focus, and the welding speed. A schematic of the process can be seen in Figure 3. In this case, an Nd:YAG laser is being used.

![Figure 3](image1.png)  
**Figure 3.** Schematic representation of the transmission laser welding process using infrared dye.

RESULTS - For these experiments an Nd:YAG laser, with a 7mm diameter focal spot was used at powers between 50 and 100 watts. The welding speeds were in the range 500-1000mm/min. Figure 4 shows continuous and hermetic overlap welds made in the waterproof fabric Goretx\textsuperscript{TM} using this technique and an Nd:YAG laser beam of approximately 100W in power. The welding speed was 500mm/min.

![Figure 4](image2.png)  
**Figure 4** Continuous overlap welds made using infrared absorbing dye in the fabric Goretx\textsuperscript{TM}

Figure 5 shows a cross-section through a similar overlap joint between two pieces of Tactel\textsuperscript{TM}, a nylon based fabric employing a polyurethane top layer, welded at 1500mm/min.

![Figure 5](image3.png)  
**Figure 5.** Cross section of a joint made utilising infrared absorbing dye. in the fabric Tactel\textsuperscript{TM}.

<table>
<thead>
<tr>
<th>Material Colour</th>
<th>Thickness (mm)</th>
<th>Peel Strength (N/mm)</th>
<th>Lap/Shear Strength (N/mm)</th>
<th>Parent Strength (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown</td>
<td>0.19</td>
<td>0.70</td>
<td>2.08</td>
<td>8.47</td>
</tr>
<tr>
<td>Orange</td>
<td>0.23</td>
<td>2.16</td>
<td>5.22</td>
<td>13.95</td>
</tr>
<tr>
<td>Bronze</td>
<td>0.16</td>
<td>2.07</td>
<td>2.76</td>
<td>9.38</td>
</tr>
<tr>
<td>Yellow</td>
<td>0.41</td>
<td>4.40</td>
<td>6.79</td>
<td>16.12</td>
</tr>
</tbody>
</table>

**Table 1.** Results of mechanical testing on a range of woven fabrics.

The peel and lap/shear tests were performed on 25mm wide samples at a test rate of 5mm/min. The test results are quoted as the maximum applied force per mm of seam. It can be seen that, as a percentage of the strength of the parent materials, values between 25 and 40 percent were obtained for the welded joints in a simple lap configuration.

DEDUCTIONS - Polymer fabric materials can now be laser welded using near infrared absorbing dye as a mechanism to produce heat and localised melting. The welds produced are cosmetically appealing and the
upper and lower surfaces of the material are unaffected by the process. In mechanical testing, joint strengths of between 20 and 40 percent of the parent material strength have been achieved, in a simple lap joint.

The welding process is efficiently achieved using the very compact diode laser sources now commercially available, and lends itself easily to high levels of automation.

The process of laser welding using an infrared absorbing dye has been given the trademark ClearWeld™. In addition, patent protection has been initiated by TWI on this process. Gentex Corporation, who manufacture suitable dyes for the process, are licenced by TWI to exploit the ClearWeld™ technique.

**ADHFAST™**

Nuts, bolts, rivets and screws are probably the most common and, for many people, the most trusted ways that industry employs to assemble, create and retain complex structures. The range of structures is vast and the thought of replacing some or all of the mechanical fasteners used, with glue, especially in a structural or load-bearing context could be regarded with concern. However, despite such scepticism, adhesives are playing an increasingly important role throughout the engineering world, a role that will continue to grow in both volume and range of applications. The primary drivers behind such growth are the increasing interest in mixing materials to maximise performance (e.g. plastics, metals, ceramics, composites etc) and the advantages adhesives offer over traditional jointing techniques. These advantages can be broadly defined as:

- Ability to join almost any material combination
- Superior fatigue properties
- Elimination/reduction of stress concentration points by bonding the whole joint area
- Ability to have mechanical properties tailored to joint function i.e. rigidity, elasticity, toughness, coefficient of thermal expansion etc.
- Ability to have physical properties tailored to requirements i.e. electrical and thermal conduction/insulation and cure initiated by radiation (blue or UV light, electron beams).
- Sealing ability
- Elimination/minimisation of thermal distortion

However, despite these advantages, adhesives have suffered much bad publicity due to the perception that they are:

- A poor or weaker substitute for welding or using mechanical fasteners
- Messy to use
- Perceived to have significant health and safety risks
- Difficult to inspect directly with respect to quality control and defect assessment
- In need of complex pre- and post-processing

- Always the reason for failure (even when they have nothing to do with it!)

The idea that adhesives can fulfil a structural function, reliably and effectively has been proven many times over. For example, the brake shoes in most cars are bonded in place, aircraft rely upon adhesive in conjunction with rivets to bond and seal the fuselage, composite bonded drive shafts are used in lorries and cars etc.

Although it is often true that an adhesive bond may never be as strong as the parent material, the design of the joint can significantly enhance the overall performance of the structure. It is also accepted that the quality control (QC) behind such a bonding operation can be difficult and complex especially when the structural integrity of the joint is brought into question. This necessitates the need for skilled personnel in both the design and the implementation stages of production. Without the appropriate skills, QC will be limited and there is a greater chance of failure either though poor joint design/material selection or during the actual assembly stages.

Adhesives that cure at room temperature are usually two component that need to be mixed prior to application and the process of applying the adhesive to the surfaces of the bonding substrates can be messy and time consuming. For many structures, it is common and indeed best practice, to dry-assemble the joint first, check for tolerance before disassembly again. The adhesive is then applied before reassembly in conjunction with jigging; to hold the joint together while the adhesive cures and hardens. This linear process often requires a period between each stage, which if exceeded requires an additional operation to be added before the process can continue. In simple terms the process can be defined as follows:

1. Surface preparation on the materials to be joined. This may be a simple degrease operation but usually more complex processes are employed. For example - abrasion (hand papers, gritblast or shot blast), chemical etching, anodising, priming, use of coupling agents, flame plasma or corona discharge etc

2. Mixing and application of the adhesive. This is often a manual operation where a bead or beads of adhesive is/are applied to one or both of the surfaces with an adhesive dispenser combined with a mixing unit. To ensure complete wetting of the surfaces to be bonded, the adhesive can then be spread out evenly over the surfaces.

3. Assembly of components. The components then have to be assembled and aligned correctly. This process can be messy if excess adhesive has been used. It is also often quite difficult to achieve accurate alignment of the components without special jigging and guides.

4. Additional jigging and clamping. Such jigging/clamping is often required once the structure...
has been assembled to apply even pressure in the joint area while the adhesive cures.

5. Curing of the adhesive. Many adhesives have been formulated to cure at room temperature through reactive chemistry but there are others which require heat to react therefore necessitating the use of an oven or heating equipment.

6. Disassembly and checking of the structure. Once cured, time has to be spent removing the structure from the jigging and checking that the adhesive has fully filled the joints (visual inspection).

7. The process is then repeated for the next structure.

The stability of the pre-treated surface prior to bonding is often very low and exposure to the atmosphere or grubby hands can limit the effectiveness of the pre-treatment. Such a time window varies with pre-treatment and material e.g. anodised aluminium needs to be bonded within hours, flame treated plastic may only have minutes while some primed materials can be left ‘open’ for weeks. In addition, the working time of the adhesive before it starts to harden affects the area of joint that can be bonded.

For an adhesively bonded joint to be reliable, the bonding process must follow strict procedures by trained operators. Many companies do not appreciate the need for skilled staff and this can result in failure that in turn reinforces the idea that the adhesive is at fault rather than the process. One way in which such problems are overcome is by combining a mechanical fastening system such as riveting, bolting, clinching or spot welding with the adhesive to form a hybrid joint. The point fastening system enables a safety back-up to be built into the joint (and some visible confidence), combining this with the superiority of the adhesive joint especially in terms of fatigue, and sealing capacity.

Some of the best examples of hybrid joining are seen in the car industry where the adhesive application and spot-welding is carried out by robots.

It is from this background that the concept of AdhFAST™ arose. AdhFAST™ is a hybrid joining system that brings together the advantages of both adhesives and fasteners and in addition offers a high degree of QC with a minimum of additional operator training. In essence AdhFAST™ can take the form of a four function fastener which:

1. Locates – enables positional accuracy between components to be defined
2. Fastens – traditional function plus acts as a jigging aid during the adhesive cure stage
3. Spaces – controls the spacing between the materials to be joined, thereby enabling adhesive to be easily injected and defining the final thickness of adhesive in the joint, this second factor aids the calculation of the mechanical properties of the bonded joint
4. In addition, allows adhesive to be injected – accomplished either though a central hole or down features on the sides of the fastener.

The fastener, which can take a whole range of forms (nut and bolt, screw, rivet etc), fulfils its function as a fastener in that it locates and fastens the materials to be bonded together. The fastener is positioned such that it sits within the prospective joint away from edges and high stress areas. In addition to its normal function, the fastener contains a spacer element (a shaped washer or similar) which contains grooves or features that will allow a space to be maintained between the two spacers. In turn the fastener is designed in such a way as to allow liquid or paste adhesive to be injected through or past it and around the spacer element in to the bond cavity. The adhesive can therefore be pumped into the bondline to fully fill the joint from the inside out. Provided appropriate surface preparation has been carried out on both surfaces to be bonded, the joint will be fully wetted by the adhesive prior to curing.

By using AdhFAST™ the assembly and bonding process is simplified without sacrifice in QC.

1. Surface preparation the materials to be joined. This part of the operation cannot be changed as the type of pre-treatment defines the level of adhesion attainable to the surface of each substrate.
2. Assembly of components. The components are aligned, assembled and held together using AdhFAST™ fasteners. The structure and associated joints can be quite complex in shape and that adhesive injection allows more than one component to be bonded at any one time. A structure using AdhFAST™ will not require additional external jigging. The edges of the joint may need to be sealed which can be done in a number of ways including using adhesive release tape, using inflatable bellows or simple gasketing.
3. Adhesive injection. The adhesive is then mixed as normal and injected into the joint cavity through the AdhFAST™ fasteners. As the adhesive fills the joint, its progress can be monitored by its appearance out of the hole in the next fastener. The injection process is then continued through that fastener after sealing the previous one. The amount of adhesive that the operator is exposed to is minimal.
4. Curing of the adhesive. As described previously the adhesive cures either on its own, by heat or some other energy source.
5. Disassembly and checking of the structure. Using AdhFAST™ the only disassembly needed may be the peeling away of sealing tape, as no additional jigging is required. Visual inspection will be as usual.

Employing AdhFAST™ enables the following benefits to be attained:

- No external jigging
- Simplified dry assembly with accurate location and checks of tolerance
- Protection of pre-treated surfaces prior to bonding from excessive atmospheric exposure and operator contamination
• Minimal operator exposure to uncured adhesive
• Simplified adhesive application process
• Reduced adhesive wastage
• Accurate metering of adhesive within the joint
• Accurate bondline control
• Saving in time due to elimination of jigging assembly/disassembly
• Reduction in manpower required for the bonding process, indeed the process could be fully automated in some instances

In addition to the above benefits, AdhFAST™ offers a change in the manufacturing approach to bonding by breaking the linearity of the process i.e. there can now be a dry assembly stage followed by a separate injection stage. In reality this means that these operations could be done in different geographical locations or at different times depending upon production and manpower resources. With the correct selection of surface pre-treatment, where a bonding window of days or weeks was possible, the storage of dry assembled parts ready for bonding, with the possibility of disassembly and re-use should an order be changed or amended is made possible.

It was stated earlier in this article that AdhFAST™ was a system independent of a particular fastener design if it had the properties of location, fastening, spacing and injection. A fastener of the correct design can be produced for each application. This enables the technology to be adapted to virtually any industry sector:

• a high value, high precision titanium rivet for aerospace
• a low cost, low precision steel screw and spacer for DIY
• a modified structural nut and stud arrangement for the building trade.

The key word is system, people are unsure of adhesives as joining materials despite extensive use. However if adhesives are employed in a system which achieves a high level of QC then the majority of doubters are silenced. Probably the best example would be the advent of Gluelam® technology where simply bonding together smaller sections of wood in a controlled high quality process creates large wooden structural elements. The resultant product is used worldwide as essential supporting members in a whole range of buildings. Gluelam® is presented as a complete high quality system, the fact that they are just bits of wood glued together is not seen as a problem. The AdhFAST™ system has the potential to offer this same degree of confidence throughout manufacturing industry.

VITRESYN™

The objective of this innovation is to deposit protective coatings onto soft substrates such as aluminium and plastics and other readily abraded substrates such as glass. Sol-gel was identified as a potentially useful technology since it allowed glass and ceramics to be fabricated in room temperature solutions.

A selection of coating formulations, for glass and various metals has been developed, together with the definition of the important criteria that a coating system would have to match if it was to attain a technical and commercial acceptance. The technical hurdles that needed to be overcome before a viable coating system was achieved were also identified. These included the need to increase the achievable coating thickness from a maximum of ~1.5μm to ~10μm. This was essential, otherwise the ease of deformation of plastic substrates would always cause brittle failure in the coating. This is commonly referred to as the “ice on mud” scenario, where a hard and brittle coating is easily compromised by the soft substrate until it has a minimum degree of integrity.

Another challenge was that of existing competitive commercial solutions, with silicone hardcoats identified as the benchmark. These are routinely used on many products and have particular specific processing windows and operating performance specifications. The solution had to at least match the performance of silicone hardcoats, and preferably have less arduous processing conditions.

The route selected was to devise a method of combining the inorganic network produced using the sol-gel method with an organic network. A similar approach has been tried by other workers in the field, but gave transparency problems when the inorganic content exceeded 25%. The innovative process that has been developed minimised this problem and achieved many of the target performance values.

Whilst the development of the new technology was continued, a patent application on the fabrication process was submitted and a brand name coined. The name Vitresyn™ reflects the origin of the materials produced (the coatings are vitreous and synthetic).

Vitresyn™ coatings compare very favourably with the best silicone hardcoats. Whilst greater protection against abrasion is afforded to the substrate (as measured using industry standard Taber testing), Vitresyn™ coatings do not need a primer, and can be rapidly cured at room temperature using UV light. Since the raw materials for the Vitresyn™ process are not particularly expensive, it is likely that the commercial coating systems will be competitive with silicones. The abrasion results are shown in Table 2.

<table>
<thead>
<tr>
<th>Coating Type</th>
<th>Coating Identity</th>
<th>Substrate</th>
<th>Primer Required</th>
<th>Increase in Haze (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial silicone Hardcoats</td>
<td>SHC 1200</td>
<td>Polycarbonate</td>
<td>Yes</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>AS 4000</td>
<td>Polycarbonate</td>
<td>Yes</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>SHC 1200</td>
<td>Acrylic</td>
<td>Yes</td>
<td>7.5</td>
</tr>
<tr>
<td>Vitresyn™</td>
<td>C80A</td>
<td>Polycarbonate</td>
<td>No</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>C95A</td>
<td>Polycarbonate</td>
<td>No</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Table 2 Comparison of properties of commercial silicone hardcoats and Vitresyn™. The increase in haze was measured after 300 Taber cycles. The coatings were heated to 130°C on polycarbonate and 80°C on acrylic substrates for one hour.

Future technical developments aim to improve the properties of the existing coatings and develop new coatings for different markets, such as protecting painted metal components. The commercial considerations are related to how the technology will be made available for the large markets that exist for solution based hardcoats.

CONCLUSION

There is no shortage of problems to tackle in the world. We may already have the means to tackle them: what we need are the innovative solutions and the will to implement them. If we do not have either of these, the outlook could be bleak for individuals, organisations, countries and the global economy.

Finally, the innovation process needs good management that balances the need for good definition, resource planning, team building and commitment with the need for variety, flexibility and rapid response. It needs innovators and adaptors; it leaves scope for individual creativity; it balances pressure of time and resources to achieve agreed goals with the opportunity to develop new ideas.

ACKNOWLEDGMENTS

The authors would like to thank their colleagues for assistance and support during the development of these innovations.

REFERENCES
