Programme

10.00  Registration and Coffee.

10.30  Bioresources for Adhesives and Sealants.
James Clark, University of York.

11.00  Reach – A Driver for a Change.
Joanne Lloyd, Reach Ready Chemical Industries Association.

11.30  Friendlier Surface Treatments.
Gary Critchlow, Loughborough University.

12.00  Developments in Reduced Toxicity Sealants.
Steve Shaw, DSTL Porton Down.

12.30  Lunch.

David Packham, University of Bath.

William Hally, Henkel Product Development, Dublin.

15.15  Disassembly of Adhesive Joints for Recycling.
Allan Hutchinson and Pat Winfield – Oxford Brookes University.

15.45  Discussion, close and coffee.

This one-day symposium is one of an on going series organised by the Society for Adhesion and Adhesives.

This particular event is organised jointly with the British Adhesives and Sealants Association - BASA.
The next symposium is due to be held at the SCI on Wednesday 10th April 2008.

Details from
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It is with great sadness that we have to announce the death of Professor Keith William Allen, who died suddenly at home on Sunday 2nd September 2007.

Keith had reached the grand old age of 81 and was well known to the global adhesive community; especially with his links to the original series of international conferences on adhesion and adhesives: originally held at The City University, London and latterly at Oxford Brookes University.

Keith was also one of the 'founding fathers' of what is now the Society for Adhesion and Adhesives.

Keith was a stalwart supporter of our one-day events and would normally be seen manning the “registration desk” in the morning.

Keith will be sadly missed by us all.
Bob Adams Committee
Keith Armstrong Press
Mark Ashcroft QinetiQ
Rajinder Atwal National Adhesives
Paul Bancroft Hodgson Sealants Ltd
Paul Baxter Arizona Chemical By
David Birkett Henkel Adhesive Technologies Committee
John Bishopp Committee
Malcolm Bowditch Synthomer
Gary Chaplin Pafra Adhesives Ltd Committee
Robin Chivers University Of York Committee
James Clark Loughborough University
John Comyn Committee
Gary Critchlow Loughborough University
Alison Davies Bostik Ltd
Richard Ellis National Adhesives
Sonia Evans Bostik Ltd
Linda Fernee Dstl Porton Down
Katheryn Ford AWE Plc
William Hally Henkel Product Development
Alan Hanbury Henkel Loctite Adhesives Ltd
Lois Hobson ICI
Malcolm Holley Hodgson Sealants Ltd
Allan Hutchinson Oxford Brookes University
Natalie Jamieson AWE Plc
Wei Kong National Adhesives
Joanne Lloyd Reach Ready Chemical Industries
Granville Makin Lake Chemicals & Minerals
Ryan McCurdy Oxford Brookes University
Gary Meyrick Bostik Ltd
Steve Millington QinetiQ
Kevin Morris QinetiQ
Christine Mullock Bostik Ltd Committee
John Murdock Icap-Sira Chemicals Italy
Peter O'Loughlin University Of Bath Committee
David Packham Rakem Ltd
Jim Palmer Celanese Emulsions Gmbh
Kieran Rafferty Sika
<table>
<thead>
<tr>
<th>Name</th>
<th>Company/Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andrew</td>
<td>Scott Bostik Ltd</td>
</tr>
<tr>
<td>Steve</td>
<td>Shaw Dstl Porton Down</td>
</tr>
<tr>
<td>George</td>
<td>Sheridan JSF Material &amp; Process</td>
</tr>
<tr>
<td>Sam</td>
<td>Smith National Adhesives</td>
</tr>
<tr>
<td>John</td>
<td>Somers Bostik Ltd</td>
</tr>
<tr>
<td>Corinne</td>
<td>Stone Dstl Porton Down Committee</td>
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<tr>
<td>Dave</td>
<td>Tod QinetiQ</td>
</tr>
<tr>
<td>Simon</td>
<td>Torry Bostik Ltd</td>
</tr>
<tr>
<td>Pete</td>
<td>Webb Dstl Porton Down Committee</td>
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<tr>
<td>Helen</td>
<td>Weston Beardow Adams</td>
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<tr>
<td>Stuart</td>
<td>Wetherell Arizona Chemical Bv</td>
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<tr>
<td>Ian</td>
<td>Wilkinson Oxford Brookes University</td>
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<tr>
<td>Pat</td>
<td>Winfield QinetiQ</td>
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<tr>
<td>Phil</td>
<td>Wylie Loughborough University</td>
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<tr>
<td>Keith</td>
<td>Yendall Bostik Ltd</td>
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</table>
The challenge for chemical manufacturing is as great as any faced by industry. The chemical industry that has been so effective for much of the 20th century is now under enormous pressure to change in almost all aspects of how it operates. The last years of the 20th century saw an exponential growth in legislation affecting chemical manufacturing processes. Manufacturing was also facing higher costs for energy and for the disposal of hazardous waste, both of which were increasing at a rate greater than the price of their products.

There is also a dramatic increase in public and government concern in the human and environmental safety of products, concerns that are now being taken up by downstream users. This is largely consequential of general concerns over the environment and a steady stream of reports largely from NGOs, over the detection of synthetic chemicals in animals and humans (as much a result of improvements in analytical science as any increase in exposure to chemicals). Throughout both of these periods we have seen a rapid increase in the cost of primary raw material of the organic chemicals industry - oil. We need to look for alternatives to oil for long-term, sustainable chemical manufacturing.

Thus chemical manufacturing faces an unprecedented degree of pressure, at all stages in the lifecycle or supply chain of chemical products (Figure 1).
Ultimately, we need to be able to manufacture a very wide range of chemical products including components for adhesives and sealants, and for a rapidly growing market especially through the growth in consumer demand in Indo-China. These products will be subject to increasing scrutiny in terms of their toxicity, persistence and degradability and their manufacturing processes will have to be carried out under ever-tighter controls. In all cases we will need feedstocks and if we are to build up a family of green and sustainable chemical products then these feedstocks must come from resources which are renewable on a realistic timescale. The lifecycle for the production of oil is millions of years while our consumption of the bulk of the accessible portion of this will be measured in 100-200 years, a difference which dramatically illustrates the unsustainability of oil as a major industrial feedstock. The only source of carbon which is available in sufficient volume and with a sufficiently short lifecycle is from plants including trees, grasses, algae and crops. The term often used to describe the non-food part of this is “biomass”

The biorefinery is the term used to describe the facilities that will carry out the conversion of biomass into energy, chemical and material products. In a typical biorefinery today, a raw material such as trees are converted into both material and bioenergy products. In the next generation biorefinery, the feedstock will be fractionated further into valuable components by extraction, fermentation and controlled pyrolysis, as well as by more traditional methods and the chemical products may be further converted into higher value products (e.g. esterification of fermentation acids) It is essential that we use green chemical technologies and apply green chemistry principles throughout the biorefinery so as to minimise the environmental footprints of its products (Figure 2).
A good example of an abundant and successful crop in the UK and elsewhere is wheat. It also serves as an illustration of the diverse chemical and materials potential in agricultural products, and how green chemical technologies can be used to maximise their extraction and utilisation.

There are two approaches to developing new greener and sustainable adhesives and sealants:

- Direct use of bio-extracts and bio-components in formulations
- Synthesis of new or existing products starting from bio-platform molecules and using green chemical methods.

Having considered the current position and the multiple drivers that are forcing change, I will look at examples of greener and sustainable products based on both of these approaches.

References

1. J H Clark, Green Chemistry today (and tomorrow), Green Chemistry, 2006, 8, 17
2. D J Knight, Regulation of Chemicals, RAPRA Review Report 181, 16 (1), 2006
7. FEI Deswarte, JH Clark, AJ Wilson, JJE Hardy, R Marriott, SP Chahal, C Jackson, G Heslop, M Birkett, TJ Bruce, G Whiteley, Toward an Integrated straw-based Biorefinery, SCI, Biofuels, Bioproducts, Biorefineries (2007), DOI: 10.100/bbb
REACH – A driver for change?

Dr Jo Lloyd, REACHReady Technical Director
enquiries@reachready.co.uk

REACH, the EU regulation for the Registration, Evaluation and Authorisation of Chemicals that came into force in June 2007, has one key central aim: to protect human health and the environment from the potential risks arising from the use of chemicals. It represents the latest step in the next generation of EU Health, Safety and Environmental legislation and is going to affect almost all businesses that operate within the EU. Dr. Jo Lloyd, Technical Director of REACHReady Ltd, a subsidiary business of the Chemical Industries Association, talks us through the effects on the supply chain. Building upon the CIA’s rich knowledge and experience of the regulation, REACHReady has the world’s longest track record for helping companies from all industry sectors, from all around the world to deal with the REACH regulation.

REACH – a force for change?

Legislators these days like to respond to public opinion. In the past the general public were concerned about industry’s activities at a site level and a whole raft of regulations now control manufacturing operations. Public focus in recent years has begun to shift - to concern about our products, the affects upon our health and the impact on the environment. We are now seeing the introduction of a new generation of legislation as a result - regulations such as WEE and RoHS are already affecting the electronics sector. And now we have REACH - perhaps the most complex, far-reaching and costly piece of regulation ever to originate from Brussels. REACH has the potential to impact us all, the textile industry being no exception.

REACH has been a long time coming, its origins date back to 1998 and it intends to achieve its goal by requiring business to fully ascertain the risks posed by the use of chemicals. In simple terms (and nothing is simple about REACH!) anyone that makes, imports or uses a chemical within the EU will need to consider his or her obligations. These obligations can range from ensuring that your supplier includes your use of their substance in its REACH dossier, to generating expensive toxicological data, to needing to undertake research and development activities to discover “safer” replacements for certain hazardous chemicals.

But what impact will REACH have? Much has been written about the various impact studies and cost estimates - ranging from €2 billion to over €11 billion - and at this stage it’s impossible to know which is right, though some say these are underestimates! The EU chemical supply chain is highly complex and diverse; coming up with concrete figures therefore is a very difficult thing to do.

That said, REACHReady has been helping companies deal with the REACH regulation for some time now and has had the privilege to gain some unique insights into how REACH may work in practice. Writing from a practitioner’s perspective, working with businesses on a day-to-day basis enables REACHReady to form some general conclusions...

Firstly it’s true to say that REACH challenges every part of industry, no matter how it is defined. Indeed REACHReady has found that almost every manufacturing company (i.e. not just chemical businesses!) within the EU is affected in some way and that whilst manufacturers and importers of chemicals will bear the brunt of REACH, it is the downstream user that suffers most of the unintended consequences – for example REACH may require you to substitute one of your vital raw materials but you may not be in a position to do so.

For all firms directly affected, REACH will present a major cost burden and for the vast majority this will directly impact the bottom line. Few firms believe they will be able to pass these costs on to customers. No surprises then that our experience through interacting with hundreds of companies tells us that many will struggle to cope.
This issue is particularly acute for small and medium sized businesses and start-ups. SMEs are offered a substantial reduction in the fees they will have to pay to register substances with the REACH authorities. However I'm afraid to say that they are unable to take any comfort from this. The registration fees are insignificant when compared with the overall costs of compliance including testing, administrative activities and indirect costs such as reformulation. These are costs that SMEs will have to meet in full.

REACHReady are also finding that even for larger firms who have the financial muscle and economies of scale to cope, there will be problems in human resources terms. There just aren't enough experts out there to deliver REACH and many organisations are considering re-training their staff and diverting valuable resource away from other business activities, such as innovation, to deliver compliance instead.

And that is not all, REACH is also a driver for change to “safer alternatives” as any substances found to meet carcinogenicity, mutagenicity or reproductive toxicity criteria or that meet persistence, bioaccumulative criteria will be put under ongoing scrutiny and phased out if alternative “safer” substances exist. This is the so called A in REACH – Authorisation.

It’s not difficult to see then that REACH has a high potential for negative impact on the EU industry’s competitiveness. That’s why it’s vital that well-meaning companies do not overreact - we have learned that it’s not just responding to REACH that’s important but responding in a proportionate and appropriate manner.

Up until now we have largely been talking about chemical suppliers and supply chains located in the EU. However, for those who import or operate at the retail end of the supply chain and who import substances, or preparations (that includes adhesives) or finished goods from outside of the EU, this is where REACH can come full circle and where the responsibility to comply with REACH rests with the importer so we will see importers and retailers registering the chemicals contained in the adhesive tape they import or the child’s paper glue.

So whilst a preliminary mapping of substances and initial liaison with suppliers is vital we recommend a strict prioritisation of further effort. Users should concentrate on product critical substances, especially those from one or a few suppliers and those that have properties of concern. Resources should be focussed on these, and the risk of interruption to supply carefully assessed. It may be necessary to seek alternative supplies, to consider how a small importer can be supported in the registration task, or to initiate programmes for substitution. Only when product continuity is assured should work spread to other substances, and then again on a priority basis.

REACH then paints a pretty bleak picture, backed up by the lack of any evidence that it will improve the competitiveness of EU businesses. All the above factors put it at risk.

That said there is a growing body of opinion that says REACH also presents an opportunity!

Many downstream users of chemicals have publicly stated that in future they will only source chemicals from manufacturers or importers that have registered and support their uses in the form of exposure scenarios. It’s clear then that REACH compliance to some is going to be a major competitive advantage and may even provide a source of added value.

In addition, EU suppliers will be able to sell products to any market in the world, safe in the knowledge that they have sufficient data to comply with anyone else’s system. This will be particularly important if other countries follow the EU’s example and adopt similar legislation. It’s also not difficult to see how there will be a growing market for “safer” alternative substances. REACH plus a patented substitute substance may equal a considerable market opportunity!

So in conclusion, REACH will have a considerable impact on the competitiveness of all EU industry as a whole and for many companies its negative effects will be unavoidable. But many others will be in a position to decide whether REACH becomes a driver for change.
1 Introduction

With only a few exceptions, some degree of surface treatment is applied to all metal surfaces prior to adhesive bonding. The surface treatment applied will depend upon the requirements of the bond and service conditions that it will see and will generally be chosen on a “fit-for-purpose” basis. The minimum preparation which is usually carried out might include a simple degrease to remove processing aids, such as oils and waxes, and contaminants. However, it is recognised that the current state-of-the-art processes for structural or semi-structural metal bonding are highly complex, multi-stage treatments including conversion coating and anodic oxidation. Alternatives to the commonly-used degreasing processes are sought for many reasons, for example: established processes may not be adequate for difficult-to-remove materials; the processes may use VOCs; they can be carcinogenic or ozone depleting. Regarding the higher treatments, the anodising processes, in particular, are difficult, time consuming and costly to carry out. There are also legislative drivers which make utilisation of the more complex processes, especially those which utilise hexavalent chromium, highly undesirable. Other factors such as energy and chemical disposal costs also deserve consideration when considering the need for environmental or operator “friendly” processes.

This paper will consider a number of alternative friendly surface treatments which might be considered as drop-in replacements for the current industrial standards. The friendlier surface treatments include two simple cleaning methods, namely: seaweed-based cleaners and CO2 laser ablation. In addition, to cover the spectrum of processes, two novel anodising methods will also be discussed. These are based upon electrolytic phosphoric acid deoxidising plus sulphuric acid anodising (EPAD+SAA) and alternating current-direct current (ACDC) anodising.

2 Alternative Cleaning Methods

2.1 Seaweed-based Cleaner

A layer of organic material present on metal surfaces will, typically, give a water contact angle between 55 and 95°. If the organic layer is effectively removed the contact angle will be reduced to zero. In the present study, contact angle measurements provided a simple method to assess the effectiveness of various cleaning agents. Removal of the organic layer is important because it may constitute a weak boundary layer and because removal of a low energy surface will improve wetting by the subsequently applied organic coating.

The present study considered a range of cleaners on as-received stainless steel; the cleaners are detailed in Table 1. Note that percentages are on a volume basis. Household detergents were moderately effective in removing organic material from the stainless steel as can be seen from the much reduced contact angles, in Table 2, compared with the untreated control. However, they were not as effective as the proprietary metal cleaner Circamax 103. Of particular interest, Sea Power is a natural detergent based on seaweed and is a product of Natural Technologies International Ltd.

AES data confirmed the effectiveness of the proprietary cleaner in removing organic material. On its own, the seaweed-based detergent was not an effective cleaner but in combination with sodium hydrogen orthophosphate, it gave promising results.

As would be expected, the degree of cleaning increased with treatment time. Ultrasonics also significantly increased the effectiveness of the proprietary cleaner. For a given treatment time, the degree of cleaning was improved with ultrasonic agitation. Conversely, a given degree of cleaning could be achieved more quickly if ultrasonics was applied. The alkaline and acid-based cleaners were shown by AES to also modify the surface oxide by enrichment of the chromium in the surface oxide, the thickness of the oxide layer was reduced by both the alkaline and the acidic etches.
Table 1 – A summary of cleaners studied - Code to treatments

<table>
<thead>
<tr>
<th>Code No.</th>
<th>Process description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Untreated.</td>
</tr>
<tr>
<td>2</td>
<td>20% Circamax 103 alkaline cleaning solution 2% Domestic detergent 1 solution</td>
</tr>
<tr>
<td>3</td>
<td>2% Domestic detergent 2 solution</td>
</tr>
<tr>
<td>4</td>
<td>2% Domestic detergent 3 solution</td>
</tr>
<tr>
<td>5</td>
<td>2% NMR Sea Power 100 solution</td>
</tr>
<tr>
<td>6</td>
<td>2% NMR Sea Power 100 solution + 1% sodium hydrogen orthophosphate solution</td>
</tr>
<tr>
<td>7</td>
<td>2% NMR Sea Power 100 solution + 1% sodium hydrogen orthophosphate solution + 1% sodium metasilicate solution.</td>
</tr>
<tr>
<td>8</td>
<td>0.5% NMR Sea Power 100 solution + 1% sodium hydrogen orthophosphate solution.</td>
</tr>
<tr>
<td>9</td>
<td>5% Domestic detergent 4 + 1% sodium hydrogen orthophosphate solution.</td>
</tr>
<tr>
<td>10</td>
<td>1% Domestic detergent 4 + 1% sodium hydrogen orthophosphate solution.</td>
</tr>
<tr>
<td>11</td>
<td>20% Circamax 103 alkaline cleaner solution followed by 20% Circamax 115 acid cleaner.</td>
</tr>
<tr>
<td></td>
<td>2% NMR Sea Power 100 solution + 1% sodium hydrogen orthophosphate solution followed by a 4% sulphuric acid solution.</td>
</tr>
</tbody>
</table>

Table 2 -Summary of contact angle data

<table>
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<tr>
<th>Pretreatment Code</th>
<th>Ultronics</th>
<th>Contact angles after x minutes in cleaning solution</th>
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<tr>
<td></td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
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<td>2</td>
<td>√</td>
<td>14</td>
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<td>3</td>
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<td>23</td>
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<td>-</td>
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<td>6</td>
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<td>-</td>
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<td>8</td>
<td>√</td>
<td>53</td>
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<td>9</td>
<td>√</td>
<td>33</td>
</tr>
<tr>
<td>10</td>
<td>√</td>
<td>50</td>
</tr>
<tr>
<td>11</td>
<td>√</td>
<td>15</td>
</tr>
</tbody>
</table>

2.2 CO₂ Ablation

TEA CO₂-laser ablation has been studied to establish its effectiveness for the cleaning of hot dipped galvanised (HDG) mild steel. This laser-based process was demonstrated to be more effective than double-degreasing with ultrasonic immersion in acetone for the removal of organic contamination from a previously oily surface. In addition, the TEA CO₂-laser was shown to modify both the near surface chemistry and the topography; the precise modifications being dependent upon the degree of treatment used.

Importantly, in bond durability trials, the changes introduced to the laser-treated HDG surface were shown to provide equivalent or better joints compared with degreased adherends; see Tables 3 and 4. In the same durability trials, a commercially-available phosphate-based, wet chemical treatment was shown to provide bond durability significantly inferior to the TEA CO₂-laser. In contrast, a chromate-based process gave markedly superior bond durability.
Table 3. Initial joint strengths (kN) of SLS joints as a function of surface treatment

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Joint strength (kN), ± 1 standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double degrease</td>
<td>4.4 ± 0.08</td>
</tr>
<tr>
<td>Gardobond 250</td>
<td>4.5 ± 0.22</td>
</tr>
<tr>
<td>Gardobond 4504</td>
<td>4.5 ± 0.23</td>
</tr>
<tr>
<td>Gardobond 250+4504</td>
<td>3.6 ± 0.11</td>
</tr>
<tr>
<td>TEA CO₂-laser treatment - 10 pulses</td>
<td>3.9 ± 0.31</td>
</tr>
<tr>
<td>TEA CO₂-laser treatment - 20 pulses</td>
<td>4.0 ± 0.56</td>
</tr>
<tr>
<td>TEA CO₂-laser treatment - 30 pulses</td>
<td>4.1 ± 0.22</td>
</tr>
</tbody>
</table>

Table 4 - Mean times-to-failure, \( t_b \), of SSLS joints immersed in water at 60°C at applied loads of 0.2 and 0.5 kN as a function of surface treatment

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Applied Load (kN)</th>
<th>Mean ( t_b ) value (h), ± 1 standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double degrease</td>
<td>0.2</td>
<td>163 ± 32</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>85 ± 12</td>
</tr>
<tr>
<td>Gardobond 250</td>
<td>0.2</td>
<td>90 ± 16</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>27 ± 7</td>
</tr>
<tr>
<td>Gardobond 4504</td>
<td>0.2</td>
<td>235 ± 36</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>172 ± 6</td>
</tr>
<tr>
<td>Gardobond 250+4504</td>
<td>0.2</td>
<td>198 ± 53</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>27 ± 7</td>
</tr>
<tr>
<td>TEA CO₂-laser treatment - 10 pulses</td>
<td>0.5</td>
<td>177 ± 58</td>
</tr>
<tr>
<td>TEA CO₂-laser treatment - 20 pulses</td>
<td>0.2</td>
<td>37 ± 11</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>217 ± 30</td>
</tr>
<tr>
<td>TEA CO₂-laser treatment - 30 pulses</td>
<td>0.2</td>
<td>79 ± 30</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>162 ± 30</td>
</tr>
</tbody>
</table>

\[ 58 ± 18 \]

3 Alternative Anodising Methods

Anodising of aluminium alloys provides a surface that is corrosion resistant and which may be receptive to applied organic layers. Such functionality is achieved by engineering a hydrated oxide film with controlled nanometre-scale porosity within an adherent coating measuring typically 2 to 3.5 micrometres in thickness. The 20-30 nm diameter (\( \Phi \)) pores created during chromic acid anodising (CAA), for example, enable interphase formation with the organic layer giving excellent adhesion whilst the oxide present provides barrier corrosion protection. Idealised anodic oxide structures, such as those produced on clad aluminium alloy surfaces, are generally of uniform pore diameter with depth, albeit with some lateral branching possible. There is, however, a conflict between the requirement for good corrosion resistance, which dictates a compact pore structure with thick cell walls and small diameters, and adhesion, which requires good interlocking and a large pore diameter. The former case is satisfied by the sulphuric acid anodising (SAA) based processes with \( \Phi \sim 5 \text{ nm} \) and the latter by phosphoric acid based processes where \( \Phi \gtrsim 50 \text{ nm} \). The CAA process, in some respects, provides a compromise.

However, duplex structures offer the advantages of a large pore diameter in the outer layers of the anodic oxide and very small pores in the inner layer close to the metal to give the optimum adhesion and corrosion performance. There are a number of methodologies which might be used to achieve a resultant duplex structure. In the present study we have used two methods namely: electrolytic phosphoric acid deoxidising plus sulphuric acid anodising (EPAD plus SAA), and: alternating current-direct current anodising (ACDC). Both approaches have demonstrated the that they produce ideal bonding surfaces which is reflected in their ability to provide structurally sound joints when bonded using an epoxy primer/adhesive combination to levels equivalent to the existing CAA as indicated in a range of tests.
3.1 Electrolytic Phosphoric Acid Deoxidising plus Sulphuric Acid Anodising (EPAD+SAA)

Figure 1 shows the structure formed using an optimised EPAD plus SAA process. A number of process variables, for example, immersion times and temperatures plus acid electrolyte types and concentrations were considered to achieve this optimised structure. These will be discussed in detail in the presentation.

Figure 1 - a. low magnification FEGSEM image to show the through thickness duplex structure of the EPAD plus SAA oxide on clad 2024-T3 aluminium, and; b. the surface region at high magnification.

2024-T3 clad aluminium alloy bonded with the BR127/FM73 primer/adhesive system (Cytec) exposed to 60°C and tested using the standard wedge test configuration showed comparable results, with optimised processes, to CAA treated controls. In contrast, the SAA only treated aluminium alloy performed very unfavourably in this test due to the lack of primer penetration; see Figure 2.

![Figure 2](image)

Figure 2 - To show the results of wedge testing with clad 2024-T3 aluminium exposed to deionised water at 60 °C.

3.2 Alternating Current-Direct Current Anodising (ACDC Anodising).

Figure 3 shows the optimised ACDC structure in cross-section at various magnifications. A range of tests have been conducted using 2xxx (clad and bare), 5xxx, 6xxx and 7xxx (clad and bare) aluminium alloys. These tests include measurement of both adhesion and corrosion performance. In all cases, with all alloys, the ACDC process performed favourably compared with either SAA or CAA controls. Examples of wedge test data are presented in Table 5. Note, however, that peel, butt, lap shear (static exposed and fatigue)
tests have also been carried out, all tests indicating comparable levels of adhesion between ACDC and CAA treated alloys. Similarly, linear polarisation and other corrosion studies have shown that the ACDC process gives comparable corrosion resistance to the CAA. Importantly, the ACDC process is carried out in a weak acid electrolyte containing no hexavalent chromium. Furthermore, the total processing time for ACDC is approximately one tenth of that required to anodise to the standard CAA specification.

Figure 3 - FEGSEM images to show the structure of optimised ACDC oxides on clad 2024-T3 clad aluminium. Top image shows the through thickness, middle image the outer oxide, bottom image the inner oxide.
<table>
<thead>
<tr>
<th>AC anodising parameters</th>
<th>Exposure time (h)</th>
<th>1</th>
<th>4</th>
<th>8</th>
<th>24</th>
<th>48</th>
<th>72</th>
<th>96</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 V 120 s 35°C</td>
<td>Mean crack length (mm)</td>
<td>33.25</td>
<td>33.25</td>
<td>33.25</td>
<td>35.00</td>
<td>35.38</td>
<td>35.50</td>
<td>35.50</td>
</tr>
<tr>
<td>10 V 120 s 50°C</td>
<td>Mean crack length (mm)</td>
<td>31.33</td>
<td>31.50</td>
<td>31.58</td>
<td>32.83</td>
<td>33.33</td>
<td>33.33</td>
<td>33.33</td>
</tr>
<tr>
<td>10 V 240 s 35°C</td>
<td>Mean crack length (mm)</td>
<td>31.33</td>
<td>31.42</td>
<td>31.42</td>
<td>33.00</td>
<td>33.33</td>
<td>33.42</td>
<td>33.42</td>
</tr>
<tr>
<td>10 V 240 s 50°C</td>
<td>Mean crack length (mm)</td>
<td>33.50</td>
<td>33.67</td>
<td>33.67</td>
<td>34.50</td>
<td>34.83</td>
<td>35.25</td>
<td>35.42</td>
</tr>
<tr>
<td>15 V 120 s 35°C</td>
<td>Mean crack length (mm)</td>
<td>31.33</td>
<td>31.67</td>
<td>32.25</td>
<td>33.08</td>
<td>33.25</td>
<td>33.25</td>
<td>33.25</td>
</tr>
<tr>
<td>15 V 240 s 35°C</td>
<td>Mean crack length (mm)</td>
<td>31.92</td>
<td>32.17</td>
<td>32.58</td>
<td>33.58</td>
<td>34.08</td>
<td>34.25</td>
<td>34.92</td>
</tr>
<tr>
<td>40/50 V CAA</td>
<td>Mean crack length (mm)</td>
<td>31.50</td>
<td>33.10</td>
<td>33.35</td>
<td>33.90</td>
<td>34.45</td>
<td>34.45</td>
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</tr>
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</table>

Table 5 - Wedge crack length data to show the influence of varying the AC anodising parameters and electrolyte temperature for the ACDC process; note a 10 m, 20V DC process has been deposited beneath each AC film.

4 Summary

- Legislative, H&S and other drivers are currently in place which promote the need for friendly surface treatments.
- The requirements of a particular treatments may vary from a simple degreasing operation to providing complex but well defined surface topography and chemistry to meet the demands of structural bonding.
- A number of drop-in replacements exists today which provide all of the functionality of the industrial standards.
Various sealant types have been, over a period of many years, employed in a wide range of military and civil applications. For aircraft applications sealants are used for various applications with fuel tank sealing posing a particularly demanding environment. In such applications experience with many aircraft types has shown that this approach to fuel carriage can result in substantial problems regarding fuel leakage.

Although several types of elastomer compound can be considered for applications requiring resistance to fuels, those based on polysulphides have been employed in most fuel tank sealing operations. More recent compositions based on polythioethers have been formulated and have been considered.

Fuel tank sealants based on polysulphides comprise, in addition to the base polymer, a range of other compounding ingredients such as solvents, fillers and curatives, some of which can be regarded as toxic. In recent years attempts have been made to minimise the toxicological characteristics of sealant formulations, with much of this focused on the elimination of potentially harmful fillers such as asbestos and curatives based on lead and chromium compounds.

In an aircraft fuel tank it is important to recognise that the environment in which the sealant is required to operate is exceptionally harsh. In addition to the obvious presence of aviation fuel, other potential degradants will include water and icing inhibitors contained within the fuel, the effects of which will be superimposed on temperature extremes and dynamic fatigue loading. Under such extreme conditions, failures associated with either degradation of the bulk sealant and/or the sealant/substrate interface have been observed in practice.

With the introduction of potentially more benign sealant formulations, the extent to which such systems are able to resist the harsh fuel tank environment and effectively prevent fuel tank leakage needs to be established. A series of experiments designed to assess the extent to which the three main fuel tank fluids are able to influence ‘old’ and ‘new’ sealant formulations have been conducted and some of the results obtained are presented and discussed.
Adhesive technology and the sustainability of the environment

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Adhesion science and technology are deeply involved in contemporary industrial culture. The use of adhesives provides many attractive solutions to problems which the design engineer encounters. Among the many well-known advantages of adhesives over other joining technologies are: better stress distribution over the joint area; the ability to join dissimilar materials; the ability to join thin materials; ease of manufacture, avoiding machining operations for keyways, circlips etc.; reduction in weight and often an improved aesthetic appearance.

As an example of design efficiency resulting from the creative use of the applications of adhesion science, consider the ECV-3, a four-seater family car with the following performance characteristics:

Non-corroding body
Maximum speed: 185 km/hr (115mph)
Acceleration: 0-96 km/hr (0-60mph): 11.0 secs
Fuel consumption: 5.8 l/100km (ECE Urban Cycle) 49mpg
4.6 l/100km at 121 km/hr (61mpg at 75mph)
5.0 l/100km at 90 km/hr (81mpg at 56mph)
2.1 l/100km at 48 km/hr (133mpg at 30mph)

Weight 664 kg

These characteristics resulted from combining an aerodynamically efficient profile with a very low weight. The car's body consisted of a load-bearing "baseframe", to which unstressed panels were attached. Applications of adhesion science enabled the weight to be minimised: the baseframe was made of aluminium, bonded with impact-resistant epoxy resin, and the body panels were reaction injection moulded reinforced polyurethane. Thus the vehicle depended entirely on adhesives for its structural integrity.

Thus adhesion science and technology are deeply involved in contemporary industrial culture. Deeply embedded in this culture is a belief in the desirability, indeed of the necessity, of continual growth. This idea is traced back to Adam Smith, the Scottish Enlightenment philosopher who argued that an expanding economy would promote the wellbeing of all. Nowadays growth is often presented in quasi-religious language as necessary, not just for material prosperity, but for moral wellbeing - for "political democracy, individual liberty, and social tolerance". Thus it seems that the aspiration of every industrial corporation is for unlimited growth, involving the production of more goods, the exploitation of more raw materials and the penetration of more markets.

However, in recent years this commitment to growth has sat uneasily next to the increasing realisation that the natural environment was rapidly approaching a state of crisis. Put simply, the perceived crisis was associated with depletion of resources and with pollution.
Many natural resources on which our civilisation depends are not renewable, and some are being used up at a rate which is significant, when compared with the total reserves. Petroleum is perhaps the most obvious and important example of a finite resource which is being rapidly depleted\(^5\). Because energy generation is so dependent on petroleum (and on other finite fossil fuel resources), the energy crisis is one aspect of the crisis in material resources.

As human industrial activity has grown, the carrying capacity of the Earth – its ability to absorb the waste products (pollution) generated – has been saturated in more and more areas. The most obvious example of world-wide significance is the effect on climate of greenhouse gas pollutants, especially of carbon dioxide from the burning of fossil fuel.

The publication of *The Bruntland Report* in 1987\(^7\), the Earth Summit in Rio in 1992, and the Kyoto protocols in 1998 all served to raise consciousness in governments, industry and among the general public of the damage that human activity was causing and of the need to sustain the natural environment.

The concept of environmental sustainability presents a major challenge the "growth paradigm" of contemporary industrial culture. It is a concept fundamentally rooted in ethics and philosophy, but one which has strong technological ramifications. In this paper the implications of sustainability are first considered, and then practical consequences relating to the use of adhesives will be discussed.

**Sustainability**

Etymologically the term *sustainability* carries the implication of stability or equilibrium maintained "for ever", or at least for a very long time. This concept is consistent with the psychology of the vast majority of the human race who do not hope for the extinction of the species, but is it consistent with the practice of contemporary industrial society?

![Diagram of the cycle of production](image)

Western industry, and increasingly global industry, operates within the terms of a neo-liberal economic paradigm. Figure 1(a) taken from an elementary economics textbook\(^8\) represents the "cycle of production" from "wants" through production to consumption and...
thence on to further wants. Fundamental to the paradigm is the requirement for continuous growth, involving the production of more goods, the exploitation of more raw materials. The continuous circle of figure 1(a) might better be represented as an ever-expanding spiral depicting this requirement for sustained (i.e. unlimited) growth.

Figure 1(a) omits two important factors: the inputs of raw materials from the ecosystem and the discharge of wastes back to that ecosystem, cf. figure 1(b). The economic growth paradigm may be criticised for ignoring the implications of the Laws of Thermodynamics in respects to both these factors.

Standard economics treats inputs as if the resources concerned were infinite, which contravenes the 1st Law. The aspiration of many politicians and economists for continuous, preferably high growth aggravates the situation. It is readily shown that a constant rate of growth is, in mathematical terms, exponential growth of the form

\[ P = P_0 \exp(kt) \]

where \( P \) is the size of the economy or resource at time \( t \) and \( P_0 \) is its value at \( t = 0 \); \( k \) is the growth rate. It is clear that such growth cannot be sustained in a world of finite resources.

The 2nd Law of Thermodynamics has equally serious implications for an economic or industrial system based on continuous growth. The inputs to the system are typically of low entropy (highly ordered) and the wastes typically of high entropy (disordered), as the 2nd Law predicts. Thus low entropy petroleum is burnt to produce high entropy carbon dioxide and water.

The clear implication of these considerations is that the practice of contemporary industrial society is unsustainable: there must be limits to growth. It is interesting to note that this was recognised long ago by Adam Smith, as he is so often quoted in support of those who advocate neo-liberal free market competition.

The limits to growth argument, briefly outlined above, clearly calls into question the validity of a belief in progress, in the sense of a continuously improving material standards of living. Such beliefs are very recent in the history of humanity, but have become firmly embedded in the popular consciousness in Western industrial society over the past century or so, and are now being increasingly adopted on a global scale. With such a challenge to a deeply-held dominant social paradigm – one supported by a host of powerful vested interests – it is not surprising that the conclusions of the "limits to growth" argument are far from universally accepted. There are those who dismiss the argument as facile, countering that human ingenuity will always discover new technologies and develop new materials which will enable us to evade its stark logic. This belief is sometimes referred to as "cornucopian". Others (the majority in the author's opinion) simply do not engage with the argument, and act as if they believed that continuous growth is a law of nature, as inevitable as the phenomenon of gravity. They are unreflective cornucopians.

The crisis demonstrated by the application of the Laws of Thermodynamics to energy and material resources is made more urgent by the aspirations of the developing world to share in the West's levels of prosperity. Some perhaps consider that the growth in consumption, and consequent increase in material standard of living, should be confined to a small, perhaps to an ever-smaller, proportion of mankind, so that the crisis could be considerably postponed. Such a policy would be abhorrent to many (the author included).

The position adopted by individuals on issues of sustainability depends not so much on their interpretation of the scientific evidence, as on their personal philosophy and values. Irrespective of this, there seems to be general agreement that steps should be taken to limit environmental damage and to conserve non-renewable resources. The disagreement between "limits to growth" and cornucopia (and a spectrum of positions between the extremes) is over the urgency and the extent to which fundamental change to current practice should be made.
Environment and the impact of adhesive technology

Thus on the technical level the crisis of environmental sustainability is associated with depletion of non-renewable resources, with the large-scale use of energy derived from fossil fuels and with pollution, which includes the production of greenhouse gases. For many years adhesives technology has had an adverse impact in all these areas. The extent to which these impacts can be, and are being, reduced will now be considered.

Resources

Most adhesives are polymers which, at present, are derived from petroleum feedstocks. Clearly petroleum is a non-renewable resource. Controversy attends predictions of how long reserves will last, but there are some authorities, at least, which predict a permanent down turn in production within the first or second decade of the present century. How this will affect polymer production and use is, of course, impossible to say, but the consequences of rapidly rising petroleum feedstock prices will certainly be great.

It should not be forgotten, however, that adhesives obtained from renewable animal and vegetable sources have long been in use. Starch and gelatin-based glues are examples. Natural rubber is an important commercial material and, a rubber plantation is almost as effective as virgin forest in carbon dioxide absorption.

The pressures to move towards sustainability have stimulated much interest in developing new polymers from plant sources, often using fermentation techniques or genetic modification. Kamm and Kamm, and elsewhere Clark, have discussed various types of biorefinery for converting biological raw materials to industrially valuable intermediates and final products. Clark describes ways in which everyday chemical products, currently obtained from petroleum, could be derived from renewable biomass by fermentation or controlled pyrolysis. Unfortunately economic factors, which make no distinction between materials derived from renewable and from non-renewable resources, have sometimes inhibited their commercial success. Commercial production, by a fermentation route, of 3-hydroxybutyrate-co-3-hydroxy-valerate (PHBV) was discontinued in 1998 for economic considerations. Murphy pointed out that the free market regulations of G.A.T.T. prevented the subsidising of plant oils as a source of chemical feedstock. Oils from soy, palm, rape and sunflower have potential as precursors for lubricants, surfactants, surface coatings and polymers. Metzger and Eissen claim that European Union research and development in biotechnology "is being totally neglected" as a result to lobbying by vested interests of the European chemical industry.

There has been a lot of interest in polyhydroxyalkanoates (PHAs), which are produced within the cells of many different prokaryotic micro-organisms. PHAs are potential alternatives to polyesters from petroleum sources. Depending on the length and structure of the alkyl chain they have properties ranging from those of crystalline thermoplastics to elastomers. Some PHAs can be used for the production of biodegradable packaging materials. A survey of adhesives from renewable resources was published in 1989. PHBV, mentioned above, is of course a PHA.

In the area of composite materials interesting work is being done involving natural fibres, such as sisal, and also with renewable-based resin matrices.

Gandini and Belgacem have reported used the oxypropylation of vegetable or animal biomass residues to produce polyols which they used in polyurethane formulations to forms and elastomers with properties comparable with those of petrochemical-based equivalents.

Advances in polymer blends and composites obtained from renewable resources have recently been reviewed by Yu et al. They consider blends involving (i) natural polymers, such

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* General Agreement on Tariffs and Trade, an international free trade treaty.
as starch, protein and cellulose; (ii) synthetic polymers from natural monomers, such as polylactic acid; and (iii) polymers such as polyhydroxybutyrate produced by microbial fermentation, and report the successful development of environmentally friendly composites.

Recycling is an important means of conserving material resources. Recycling of polymers, certainly of linear polymers, is in principle possible. In practice successive grinding and remoulding may cause thermal degradation to an extent that the properties suffer. A serious problem is that feed stock for recycling may consist of mixtures of different grades and compounds of the same polymer or, worse, of different polymer types, leading to poor properties because of polymer-polymer incompatibility. The recycling of adhesives is even more difficult than of polymers in general as the adhesive is usually a small proportion of a larger artefact all of which should, in principle, be recycled. Indeed, inappropriate choice of adhesive can aggravate the difficulty of recycling the components joined.

Energy

Energy consumption is unavoidable in almost all technology. In 2005 the global primary energy use was of the order of 500 EJ/yr (1 EJ = 1 exajoule = 10^{18} joule). Based on figures from the U.S. Energy Information Administration, it is estimated that the figure will have risen to 1200 EJ/yr by 2095, figure 2. From these data, cumulative primary energy required from 2005 to 2050 is about 30,000 EJ. It is relevant to compare these figures with reserves of non-renewable energy. Various estimates are given for oil and uranium in table 1. Figures such as these serve to bring into a sharp quantitative focus the seriousness of the energy crisis.

![IPCC Primary energy use projected to 2095.](image)

Table 1

<table>
<thead>
<tr>
<th>Some estimates of energy reserves</th>
<th>Total energy EJ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oil reserves</strong></td>
<td></td>
</tr>
<tr>
<td>B.P.: Reserves</td>
<td>6000</td>
</tr>
<tr>
<td>Low estimate</td>
<td>4500</td>
</tr>
<tr>
<td>Highoppers</td>
<td>11,000</td>
</tr>
<tr>
<td><strong>Nuclear</strong></td>
<td></td>
</tr>
<tr>
<td>&lt;40$/kg</td>
<td>810</td>
</tr>
<tr>
<td>&lt;80$/kg</td>
<td>1620</td>
</tr>
<tr>
<td>With fast breeder</td>
<td>81000</td>
</tr>
</tbody>
</table>
To turn to polymers and adhesives, whether the source material is renewable or non-renewable, energy is used during its production and processing. Table 2 gives approximate energy contents of some polymers. Thus considerations of energy conservation and of renewable energy generation are very much relevant to adhesive technology\textsuperscript{37}. However, it is not just the energy involved in production and processing that is relevant: it is important to consider the environmental impact of an article from initial extraction of the raw materials, through manufacture and service use, to ultimate disposal - "from the cradle to the grave"\textsuperscript{14}. Such a "life-cycle analysis"\textsuperscript{38} may suggest that weight saving and engineering efficiency associated with the use of adhesives and composites may, by saving energy during use, more than compensate for problems over recycling and disposal.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Energy consumption (GJ/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene</td>
<td>110</td>
</tr>
<tr>
<td>Styrene butadiene rubber</td>
<td>130</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>174</td>
</tr>
<tr>
<td>Polychloroprene</td>
<td>120</td>
</tr>
<tr>
<td>Natural rubber</td>
<td>30</td>
</tr>
</tbody>
</table>

Pollution

Some authors consider the Earth's capacity to carry pollutants, to be even more pressing a problem than those of depletion of material and energy sources. Our record of replacing pollutants with less damaging alternatives is rather poor\textsuperscript{21}. Like most industrial processes, the production and use of adhesives produces pollutants which can have an adverse environmental effect. Much attention has been given in recent years to reducing their impact.

It is now generally recognised that the emission of any volatile organic compound to the atmosphere is undesirable, as they contribute to the formation photochemical smog and many are implicated in the aggravation of lung diseases such as asthma. Moreover, organic vapours absorb infra-red radiation and therefore act as greenhouse gases. Adhesives and coatings are a major industrial source of volatile organic compounds\textsuperscript{15}.

For all these reasons there is an increasing move away from using organic solvents and dispersing media both in pretreatments and in adhesives and coatings themselves.

Degreasing of metals has traditionally been done with the help of chlorinated solvents. Since their implication in depletion of the ozone layer, much effort has been devoted to developing less damaging procedures, such as alkaline solutions and organic aqueous emulsions\textsuperscript{39,40}.

Many adhesive systems formerly based on organic solvents are now produced as aqueous emulsions. Adhesives for rubber to metal bonding provide a good example. Similarly there has often been substitution of hot melt or of radiation-cured adhesives for solvent systems\textsuperscript{40}. Despite all these developments, volatile emissions associated with adhesive use remain high\textsuperscript{15}.

Increasing attention has been focussed in recent years on the effects of very low concentrations in the environment of a range of organic compounds. Many have been implicated in producing physiological change in humans and other animals\textsuperscript{41,42}. For example some mimic the action of hormones. There is evidence that residues of some
compounds are xeno-oestrogenic and may disrupt the endocrine system (Table 3), depressing the human sperm count and sometimes leading to male genital deformity. Many such compounds are used as additives in adhesives and composites and, because of their fundamental incompatibility with the polymer phase, are likely to be released into the environment. This is an area of controversy, with much dispute over the effects on humans of low concentrations of such chemicals in the environment, as opposed to their effects on test animals under laboratory conditions. At one time it was expected that the European Union "REACH" (Registration, Evaluation, Authorisation and restriction of Chemicals) regulations would oblige industry to replace endocrine disruptors with safer alternatives. However, vigorous lobbying by the Chemical Industries' Association and similar organisations has succeeded in diluting the impact of REACH, and a decision on endocrine disruptors has been postponed to a future date.

Table 3

<table>
<thead>
<tr>
<th>Compounds</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polychlorinated compounds</td>
<td>Formed in some incineration processes</td>
</tr>
<tr>
<td>Alkylphenols</td>
<td>Stabilisers</td>
</tr>
<tr>
<td>Alkylphenol ethoxylates</td>
<td>Surfactants</td>
</tr>
<tr>
<td>Phthalates</td>
<td>Plasticisers</td>
</tr>
<tr>
<td>Bi-phenols (e.g. bisphenol-A)</td>
<td>Constituent of most epoxy resins</td>
</tr>
</tbody>
</table>

Conclusions

What is the environmental impact of adhesive technology? Adhesives are mostly derived from non-renewable resources, many involve a significant energy input in manufacture or use, and most are associated in some way with emission of organic pollutants. However, as the short review above shows, much technical ingenuity has been used in developing ways of addressing all or most of these problems. Moreover, it must be emphasised that a broad view of environmental impact must be taken. It is not just a question of whether a particular adhesive manifests some undesirable feature: it is important to consider the total environmental impact of the engineering context in which the adhesive is to be used. A full "life-cycle analysis" may well find that the use of adhesive technology gives not only improved engineering efficiency in the traditional sense of the term, but lower environmental impact as well.

The extent to which adhesive technology develops in the direction of sustainability, depends not just on skilled technological innovation, it depends crucially on the society in which it the technology is to be applied. Several examples have been cited where economic criteria appear to favour the undesirable rather than the environmentally desirable. It is significant that the ECV-3, the highly efficient car discussed above, was developed as long ago as 1982, but never put into production. It might be thought that, rather than making environmental efficiency a major criterion, motor manufacturers have chosen to incorporate what Adam Smith called "baubles and trinkets" into their vehicles, adding to weight and increasing fuel consumption.

It may be that some changes to regulations associated with use of taxes and subsidies would be beneficial. That is a specialised economic question, but it is not a specialised economic issue to insist that environmental benefit should be reflected in economic criteria. That is a matter of philosophy and values. However despite what changes might be effected in this way, as long as the economic system seeks continuous (exponential) growth, adhesive technology will not be sustainable: the Laws of Thermodynamics will ensure that.
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DISASSEMBLY OF ADHESIVE JOINTS FOR RECYCLING

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Abstract

There are many applications of structural adhesives where it is desirable to be able to reverse the bonding process, for example for maintenance purposes, for reconfiguring components or for dismantling bonded components. In some sectors there are legislative drivers that are already forcing manufacturers to consider the assembly and disassembly operations associated with the design of products that can subsequently be reused, recycled or re-manufactured. The automotive industry represents one sector in which disassembly strategies for repair and end-of-life are increasingly important.

Techniques for disassembly of bonded joints include mechanical destruction, solvent methods and the use of thermal energy. The choice of technique revolves around the nature and number of the adherends, the scale and location of the components, and any specific restrictions associated with disassembly work. Some techniques lead to destruction of the bonded components whilst others are intended to provide a relatively clean separation that keeps the adherends intact. Clearly it is desirable that reversible bonding procedures do not confer any undesirable performance characteristics to such assemblies.

This paper focuses on thermal methods that cause microspheres, incorporated in either a primer layer or the adhesive layer, to expand at particular trigger temperatures. The nature of a particular microsphere system marketed by De-Bonding Ltd is discussed, together with the debonding mechanisms and associated process variables. Preliminary experimental results are presented for short-term bulk adhesive and bonded joint performance.