Along the bond line
Groundbreaking aircraft structures
Thousands of years ago man became aware that some substances are really sticky and can be used to fix and assemble parts. This discovery developed into knowledge and art of gluing or bonding, a very useful engineering and manufacturing skill to attach similar or different materials to each other.

It is quite obvious to use an adhesive substance made from plants or animals to connect wood to something else. Nevertheless in the 1930's something weird and untraditional happened: the discovery that you could actually bond two pieces of metal together with some kind of seemingly inferior polymer and that this connection was strong beyond expectation. It went even further. This primeval principle facilitated bonding of the epitome of progress, the very symbol of Modernity: aluminium. Counterintuitive is the word here. It is only logical that many engineers simply didn’t believe that a treacly substance from a tin could actually provide structure to this magical new metal of the future.

The concept of bonding metal to metal was invented in the UK, in the age when science and engineering bloomed. From then on recipes gradually improved and became more refined and precise. Fokker was an early adopter and has over 50 years of experience with manufacturing adhesively bonded aircraft structures. Some of the early Fokker F27 passenger aircraft, featuring wings with bonded wing structures are still in service. Metal bonding has proven to be a very reliable and flexible technique for metal part assembly. The thin-walled nature of metal structures turns bonding into an excellent construction method, even to the extent to which bonding more thin layers of aluminium with multiple bond lines is an attractive concept to gain quality and save weight, when compared to just metal. Metal bonding is trustworthy far beyond reasonable doubt and it is destined to develop further. Gradually new advantages of metal bonding, concerning design, production, operation, damage resistance and tolerance, have indeed been discovered. The first is bond strength itself. A bonded lap shear joint between two metal sheets can be configured in such a way that, against all odds, over-stressing will cause the metal adherents to fail, and
The major part of the Airbus A380 fuselage consists of Glare panels, which require no inspection.
The development of airplane manufacturing is an evolution of beliefs, fed by a steady increase in factual knowledge. The first airplanes were made pragmatically, merely to make them function, from materials that were easy to work and readily at hand: wood, rope, linen, a few steel bits. Then times got modern and with that the belief in the potential of metals grew quickly. Before long riveted aluminium became the technology to put your money on. It gained the bias of belief. Because of this from the 1940s onwards almost every airplane is designed as a riveted aluminium structural concept.

The birth of metal bonding happened almost simultaneously with the upcoming belief in metal structures, but was not readily accepted, for lack of trust. It took a while, but now we clearly have arrived in an episode of recognition of the full potential of combining different materials in structural design. Increasing knowledge and experience in aluminium and composites: that is what inspires Fokker. No single material is perfect in every sense. Finding the right balance is what matters. The ultimate solution is not one particular substance, but rather a way of thinking. Every design question has a different context and requires to be answered with an optimised set of properties that belong to a combination of certain materials. The proper approach is to select the best combination of materials, manufacturing and architecture for each part and for every assembly, all to best serve the customer. Metal bonded structures are a strong option. Fibre metal laminates are a good example of creating such a balanced solution, in which the engineer is neither forced to resort to one type of material, nor to a particular composite. Engineers can be perfect tailors. Their domain is where structure and material merge and where material therefore becomes subject to design and engineering rather than to choice. In this way changing context and continuously increasing knowledge determine the outcome of design solutions. It implies that all options must be kept open, sometimes until the last minute. Timing and planning can determine decision outcomes. Monolithic aluminium, or carbon fibres with epoxy resin, or aluminium adhesively bonded to titanium? Thermoplastic PPS? Bioplastics? There is no fixed answer. That is the essence of innovation.
Norman de Bruyne, an English physicist with a British mother and a Dutch father, invented metal bonding and created the first man made adhesives. The idea to develop glue for metals did not appear out of the blue. An idea needs food for thought to ripen and subsequently reveal itself as a new opportunity. One thing is needed before it can lead to another.

De Bruyne founded Aero Research Ltd to develop new solutions for airplanes. He created a wood adhesive in which the chief engineer of De Havilland got quite interested. Together they experimented with a sandwich structure that involved a balsa core. This became one of the structural principles in the Mosquito, a very successful fighter aircraft and in fact an early ‘composite’ aircraft. Its basic airframe structure consisted of wooden elements glued together. Then a new phenolic adhesive was developed to bond aluminium to balsa wood. It was named Redux. The word sounds chemical, but it simply is an abbreviation of REsearch at DUXford. To this day the brand name is in use, also for modern epoxy adhesives. The company later introduced the first film adhesive. In 1939 De Bruyne presented Gordon Aerolite, a laminate of flax roving and paper soaked with phenolic resin. Interestingly he originally wanted to use a fine fabric woven from glass fibres instead of flax, but the American glass producer didn’t want to cooperate: he expected
structural failure. Failure in judgement is what he got. Glass fibre reinforcement is everywhere now. After the war Aero Research became quite successful, producing vast quantities of adhesive for wood laminate production. The Swiss chemical giant CIBA bought the company. The first aircraft producers to take up use of adhesives for carrying structures were English. De Havilland daringly developed the Comet, the first passenger jet with a pressurised fuselage. Adhesives played an important role in the wing and fuselage structure, but design flaws in the overall detail design of the aircraft unfortunately overshadowed the excellent performance of the bonded joints, slowing down the proliferation of the metal bonding technology. As far as bonding connections were concerned: they remained intact for years on end and contributed to the legendary durability status of Redux 775 adhesive.

Striking similarity between De Havilland Mosquito production in wood, in the 1940’s, and current panel assembly at Fokker Aerostructures
Rob Schliekelmann, one of the visionaries of Fokker, adopted bonding. It became one of the Key Technologies of the company. He recognised the main advantages of more efficient production, improved fatigue resistance and better distribution of forces from the very beginning. His true understanding of the technique’s nature readily led Fokker customers to accept adhesive bonding.

The extensive use of bonding made the Fokker F27 Friendship (1955) and its upgrade the Fokker 50 very respected successors of aircraft like the DC-3 ‘Dakota’. They were a huge economic success. This workhorse is still being operated in various regions of the world, often under harsh conditions, which is excellent evidence of the concept’s durability and reliability. Obviously adhesive bonding was applied in the Fokker jet aircraft as well, starting with the F-28 Fellowship in 1967 and its successors the Fokker 100 and Fokker 70 twin jets. The wing and fuselage panels in which basic skin, doublers and stiffeners are assembled by adhesive bonding have become a Fokker product-technology combination that Fokker marketed successfully as a tier one supplier to many of its customers ever since.

The Fokker adhesive bonding technology has been and still is continuously improving in every respect to meet higher demands on technical and economic performance. The initial application of phenolic adhesive as a two-component system was cumbersome. From the early 1960s onward film started to replace
the jars and cans of treacly glue and powder and the process became much better controllable. Phenolics are thermosetting resins that cure through a condensation reaction, producing water that needs a way out during processing. This implies a limitation to surface sizes that can be bonded. Although phenolic systems do show endurance, epoxy resins allow tuning to a wider range of different requirements. In structural bonding epoxy resins currently have the edge over phenolics. Properties such as curing temperature, as well as strength, brittleness, ductility and heat resistance can be tailored to many different applications. When the curing process is proceeding, epoxy resins have a very low viscosity, which is an advantage when far away surfaces are difficult to reach. Epoxy adhesives with low viscosity are supported by a polyamide scrim: a curing reinforcement that also contributes to structural quality. In interior applications phenolic systems prevail because of their better fire resistance.

F27 fuselage and wings belonged to the first bonded aluminium aircraft structures
Nano grip

It is a well-established fact that bonded aluminium structures can be trusted to function for years on end. From early on it was clear that adhesives do a good job. Thanks to the development of measuring instruments it is only now that it gradually becomes clear how the bonding system works. Intuition and empirical evidence are replaced by knowledge.

Aluminium that is going to be bonded gets a thorough pre-treatment. The surface has to be prepared for an adhesive to attach itself to. First a solvent degreases it, next the surface is pickled to remove the ‘old’ natural oxide layer and subsequently anodised to form a well controlled oxide layer. The procedure is familiar, but when anodisation, an electrochemical process in an acid, was first executed in 1923, the main, vaguely defined, purpose was to protect aluminium against corrosion by building up a thin layer of aluminium oxide, or alumina as it is commonly known. Over the years it became an familiar technology and requirements for process parameters got clear through research. Production parameters were basically clear. Nevertheless researchers had to make assumptions on oxide density, constitution of the layer, and the size and shape of pores.

It was not until recently that SEM (Scanning Electron Microscopy) reached a sufficient level of magnification and resolution to reveal in detail what actually happens during anodisation. Apart from what the images tell us about the process, they are simply stunning. They show a structure with definite honeycomb characteristics. In some instances pores are on the tops of tiny ‘tree trunks’ in a nanoscale ‘rainforest’. And their density is phenomenal. Adhesive can find its way into tens of millions of pores per square millimetre and firmly attach itself. It is a level of precision that rivets will never ever reach.

The effect of process parameters is much more clear now. The layer grows upward from the barrier, the boundary between aluminium and alumina. Voltage defines pore size: the higher it is the wider the pores. This implies that pores on top of the oxide layer have a slightly smaller diameter because the current takes SEM images of anodised structure analysed by computer (right) to determine nano-scale definition of cavities.
some time to get to its maximum. Another characteristic is that the concentration of aluminium in the alloy determines the definition of the structure. Clad aluminium, for instance, is likely to produce a smooth structure with columnar pores, whereas bare aluminium with relatively low aluminium content will result in an irregular spongy alumina layer. The average pore diameter tends to be around 20 nanometres in a normal anodising process. Metal bonding appears to be large scale nanotechnology. Until recently no one was aware of that.
To understand the principle of bond function: take two times two similar plates of aluminium. Bond one pair together, with an overlap, and rivet the other, with the same overlap proportion. Now load the two contraptions, which are identical except for the attachment, with a tension force each. Adhesive will spread this disruptive power over the interface between two bonded parts, thus reducing its effect. When compared to riveting stress levels are much lower, for the two layers held together by rivets are simply not bonded. They rather act like scissors that try to cut rivets in two. All forces pile up at the edges of the holes that contact the rivets. As a result the bonded structure is stronger. Replace tension by compression and another effect will make itself known: a riveted structure will start buckling at a lower load, again because the parts are not really attached to each other. There is ample opportunity for them to deform from underneath the heads of the rivets. Again bonding is the winner.

An old argument against aluminium bonding is that adhesives are not as strong as the metal. That may be true, but this is not the point. Adhesives reduce the stress to a level that they can easily survive under standard conditions. It is always better to test and compare integrated solutions rather than to make judgements based on analysis of material properties of separate ingredients.
Fatigue is aluminium’s main weakness. The load doesn’t have to be near the level of material strength, but when it is varying with a sufficient rate, after a certain time tiny cracks will start to appear. Next they will slowly grow and diminish the amount of stress the metal can handle, until on some fatal moment there is not enough connection left over to deal with even a moderate force. The metal will break.

The advantage of bonding, apart from being a convenient way to connect parts, is that an adhesive will stop fatigue cracks from growing. They will still pop up and maybe start to propagate a tiny bit, but they are not able to cross the adhesive ‘swamp’. The relatively soft polymer almost literally removes the edge of a crack and thereby reduces stress.

Because of this phenomenon it can be smart to not just bond parts, such as stringers and skin, together, but also to compose thicker attachment elements of bonded layers of aluminium. Building up a structural element like this resembles 3D printing, in the sense that a part is made through addition, stacking up layers, rather than milling away what is not needed. The translation of a one material part into a layered structure requires careful engineering. For one thing the thickness of bonding layers doesn’t join the scale game: one can choose to increase the thickness of aluminium, but adhesives have rather fixed thickness requirements.

Looking at bonding from yet another angle it is a method to produce large skin parts in which the adhesive contains layers of unidirectional glass fibres. Now we are talking fibre metal laminates, or Glare. Fibres provide even better protection against crack growth, because they remain intact when the crack is moving past and prevent it from getting wider. Glass fibres act as a stubborn distributor of forces across crack flanks. This so-called ‘bridge-effect’ reduces the stress in the crack hotspot, the place where all this awful tearing apart happens. Glass puts a true break on crack growth.

A fatigue crack is a knife edge turned inside out. Adhesive (left) renders the edge too blunt to reach the next aluminium layer. Glass fibres (right) are strong enough to bridge the gap (‘bridging effect’).
Complete tail section bonded in one go with cold curing adhesive, in a labour saving elaborate mould

Other options in bonding have made their entrance as well. It is obvious that bonding without the need of using an autoclave is interesting. As experience with this type of attaching parts together is increasing, other advantages have revealed themselves. Assembly with the help of an adhesive can render a lot of drilling and riveting preparation work superfluous. This technology, BASSA, short for Bond Assisted Single Step Assembly is a combination of bonding and shimming with a thixotropic cold or hot curing adhesive. The bonding agent can fully compensate small structural imprecision. BASSA requires extensive tooling, but labour costs are relatively low. Fokker Aerostructures applies this promising technology to connect the complete upper and lower skin of a control surface or an entire tail to the inner substructure of spars and ribs. BASSA, this highest level of bonding to create full assemblies, is in use for Gulfstream fuselages. In primary joints adhesive bonding can be combined with blind riveting, to achieve ultimate strength. Rivets alone would limit maximum load. BASSA is another important building block for future aircraft.
For bonding aluminium Fokker Aerostructures operates two kinds of production lines. One is strictly for adhesive assembly and the other involves glass fibre. These are part of unidirectional reinforced adhesive film, which serves to produce Glare metal fibre laminate parts. The presence of glass is the crucial difference.
Black bags containing prepared rolled aluminium sheets for Glare lay-up

Metal bonded parts are cut into shape, stretched and tempered, to tune their crystal proportions and arrangement. It is basically the same as traditional production of aluminium parts for riveting. The required thickness may vary and saving weight is a matter of leaving out sheet where it is not needed. Moreover, because of this layering principle combining different alloys is simple. The outside skin can for instance be an Al2024 alloy, which is less sensitive to fatigue, whereas the inner layer could be a stronger, but slightly more corrosive Al7075 plate.

Glare parts are usually much larger than bonded parts, much larger in fact than standard aluminium plate sizes permit. After all Glare is about assembling very large skin parts in the range of 30 sq. metres, including stiffeners. The raw material is very thin (0.2 - 0.5 mm) rolled sheet. The preparation for further production consists of unrolling, cutting, pretreating, and consequently rolling up the skin elements again, protected by a layer of paper. A typical Airbus A380 panel is built from 22 of these elements.
The principle of assembling parts prior to bonding is quite simple: just stack elements and layers on top of each other, with the proper pieces of adhesive film between them. In practice the difficulty is in acquiring the right level of precision in a sufficiently clean environment. Parts to be bonded are placed in jigs, mostly by hand, and different layers get positioned correctly with the help of pins. Large relatively flat surfaces are layered with support of lasers that project the right shapes and positions on the material in green light. Here is an unexpected reminiscence of procedures in the graphic industry. During lay-up the adhesive is just a film, from which protective foil has to be removed. Obviously the trade-off between hand lay-up and automation depends on production volume. It is likely that in the near future robots will gradually take over this kind of work.
The position of consecutive layers is defined with laser projection.

After positioning all these neatly prepared parts are placed into the autoclave to be united by heat and pressure. When they come out the result looks smooth. It is an advantage one is inclined to overlook, but when clients, occasionally celebrities, come to have a look at the making of their newly purchased plane, they tend to feel comfortable with slick looking aircraft parts in a quiet environment.

Large autoclave for curing completely assembled A380 Glare panels.
Saving weight and cost are the main forces behind innovation in the aerostructures industry. These parameters are rooted in environmental effects. It is a domain where the relationship between economy and ecology is transparent. That may be the reason why air travel is quite efficient when compared to other forms of transportation.

Production systems for aircraft structures still have a lot to gain in the field of environmental effect. For one thing it requires a considerable amount of energy. Chemical pre-treatment is currently getting attention because of the substances involved. The number of chemicals we like to ban from our industry is growing. Particularly chromic acid, which is used to pickle and consequently anodise the metal, is due to disappear and be replaced. Fokker Aerostructures is currently developing a new line of pre-treatment. The successor is likely to be a very similar method with different chemicals, but other options have announced themselves and could find their way to the aerospace world. In the automotive industry surface treatment is getting physical through the use of plasma. This type of development is quite interesting since the desired effect of whichever treatment it will be in the future, now is more thoroughly known than ever. We have passed the stage of ‘see if it works’ and have arrived in a situation where we can establish if the oxide structure looks just right through a powerful microscope. Bonded structures have many advantages in production, functionality and keeping the weight and aircraft fuel burn low, but taking them apart and recycling them is still a hard nut to crack. The basic alternatives are of course to do it mechanically, thermally or chemically - they are being studied, but because of the high structural quality one could also argue to try and reuse airplane sections for different purposes. After all, compared to other industries the total production mass of airplanes is not very large. Seen from the viewpoint of innovation, it is clear that current structural solutions are not final. Some fibre-reinforced bridges now consist of renewable polymers. Something similar could happen in aircraft production.
Glorious Glare

Fibres to enhance the quality of aluminium have been under consideration for quite a while. The original idea was to bond aluminium with aramid fibres. They became the main ingredient for a new composite named ARALL, short for ARamid Aluminium Laminate. It got patented in 1981. ARALL, however, required extra handling during production, to deal with residual stress. Switching to glass fibres solved this issue and created the baseline for Glare, which got patented six years later. For a fuselage structure, fatigue resistance against loading in two directions is required. It is possible to combine unidirectional reinforced adhesive layers that are positioned in different directions. Fibre metal laminates with these bi-directional reinforcements are ideal to withstand the forces in fuselage skin. Implementation of such a new structural principle takes years. Intensive testing did demonstrate that Glare features good impact and corrosion resistance. Since it is aluminium it can deal with lightning strikes and because of the glass fibres it is quite good at containing flames in case of fire. The composite in between aluminium blocks corrosion as well. A very important advantage is that its production assembly and repair do not really differ from that of aluminium. Since the aluminium and glass reinforced epoxy layers form themselves in the mould, the differences in formability of metal and composites are easily handled. All these benefits come with an extra plus: Glare’s density is about 10 percent lower than that of aluminium. The actual density can vary, depending on lay-up design. All in all it was just a matter of time for an airplane company to start applying fibre metal laminates. Airbus’ decision in 2001 to use it for the A380 fuselage meant Glare’s crucial breakthrough. As a true hybrid its functional advantages are less radical than those of fibre reinforced polymers. In many aspects Glare can simply be treated as a kind of aluminium. Nevertheless Glare is lighter and much more reliable than aluminium on the long run. Its impact resistance, particularly against bird strike is proving its value in the entire front end of the A380 tail.

GLARE VS. ALUMINIUM COMPARISON RATIO

<table>
<thead>
<tr>
<th>Property</th>
<th>Glare</th>
<th>Aluminium</th>
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<tbody>
<tr>
<td>Weight – density</td>
<td>0.85-0.90</td>
<td>0.70-0.85</td>
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<tr>
<td>Strength</td>
<td>1.0-2.0</td>
<td>3.0-100.0</td>
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<tr>
<td>Fatigue</td>
<td>1.0-2.0</td>
<td>1.0-2.0</td>
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<tr>
<td>Damage tolerance</td>
<td>1.0-2.0</td>
<td>1.0-2.0</td>
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<tr>
<td>Impact resistance</td>
<td>5.0-50.0</td>
<td>5.0-50.0</td>
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<tr>
<td>Flame resistance</td>
<td>1.5-2.5</td>
<td>1.5-2.5</td>
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<tr>
<td>Lightning strike</td>
<td>100.0-150.0</td>
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<tr>
<td>Corrosion resistance</td>
<td>1.2-3.0</td>
<td>1.2-3.0</td>
</tr>
<tr>
<td>Repairability</td>
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<td>Maintenance</td>
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In theory it is not impossible to bond an entire airframe in one go, to avoid all bolts and rivets. It would not be easy though, or cheap. This extreme example does bring forward the two main limitations of the use of hot curing adhesives: complexity and size.

The more parts and layers have to be bonded together in one go in the autoclave, the more complicated the curing preparation will be. A complete tail section, for instance, would require a huge, heavy and very expensive jig, which will have to include hinging or detachable pieces with clamps and bolts and things. And increasing knowledge

Limitations

Taking part in a large primary structure is the highest ranking achievement for a laminate. If it can do that it can do virtually anything. Because of its high impact resistance Glare can be applied in leading edges that may suffer from bird strike or other kinds of impact. The A380 tail leading edges consist of Glare. There may be interesting potential in the fact that Glare is a glass reinforced adhesive polymer covered by a metal, which naturally conducts electricity. An integrated de-icing application is currently being developed and there may be more fancy opportunities, such as boundary layer control through static electricity. Investigations on Glare so far show, that the hybrid generally performs better than metal without glass fibres. Its compatibility with aluminium implies that principles for design and production development are familiar. Yet designing the directionality of the fibres in a certain way determine its mechanical properties. This is where the two faces of the Glare-hybrid turn interesting. Originally fibres were included to enhance fatigue resistance in aluminium, but aluminium also works to the advantage of the glass fibre reinforced adhesive it encloses. Two layers of glass fibre film with different directions together form a very thin composite, but the sum of fibre directions still results in anisotropy when it comes to force distribution. Here aluminium functions as a stress equaliser. When considered in this way, in certain situations fibre metal laminate can result in a thinner structure, which saves weight when compared to a pure polymer composite. You could define Glare also as an ultra thin aluminium reinforced polymer glass composite.

Induction welded flap edge with clean seams.

Increasing knowledge

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the more complicated tooling is, the more vulnerable. Moreover the autoclave will have to be sufficiently spacious inside. Once taken from the jig after curing you would have this inert big structure that would need transportation. Inside a plant this is not uncommon, but to move it elsewhere, to another country for further assembly, could lead to over stretching the system. Currently it already is at its limits. Careful production design is needed to optimise the balance of investments and process.

Fokker Aerostructures designed Glare fuselage skin plates for Airbus A380 for road transportation, with such a size that they fit upright inside a container on a low loading trailer. This vehicle takes the containers to a nearby harbour. Here ships take over and bring them to North Germany where Airbus assembles fuselage sections to be transported to the south of France for final assembly.

Glare design

Since Glare is a composite, it entails a lot of freedom for designers to integrate the right properties for required functionality for varying load conditions all into one advanced structure. Overall thickness, number of layers, alloy composition, number and directionality of glass film layers, they can all vary within the design of one skin panel. With the help of software structural efficiency can be optimised.

Because of layering integration opportunities are abundant. One can for instance integrate stiffening layers between the aluminium plates. The limitation of sheet width provided by aluminium suppliers can be overcome by creating overlapping structures, so-called splices, in their cross-section comparable to brickwork. These overlaps need to be quite precise, in particular along edges where the skin panel needs to be attached to the main structure through rivets or bolts. For no matter how advanced the possibility to fine-tune Glare properties to function is, classic mechanical engineering remains part of the deal.
When a Glare panel is ready, fresh from the autoclave, it needs to be thoroughly checked, for it is a complicated hand-made structure. For that purpose Fokker Aerostructures employs an ultrasonic scanning system. Every skin panel is checked entirely, millimetre by millimetre, to see if there are no suspicious looking loose fibre ends between the aluminium layers, or unwanted pieces of protection material. Ironically such an advanced inspection system is not necessary when Glare is damaged through impact. The dent is a good indicator for the shape and the size of delamination. It always stays inside the borderline of aluminium deformation. The repair procedure is traditional.

Ultrasonic scanning robot operating with sound wave guiding water jet, to detect faulty production details

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Scanned image showing area with air enclosure
Continuous innovation

Fokker operates at the forefront of aircraft innovation. This is a crucial strategy for a supplier in global aircraft industry. In the continuous process of functional improvement, weight and cost reduction, and the evolution towards sustainable air transport, lagging behind is no option. For metal bonding and the development of metal fibre laminates this implies continuous improvement and looking for the most intelligent combinations of material properties, from the nanometre scale to large aircraft sections. Continuously increasing insight and adaptation to changing circumstances will keep on improving structural quality. In a system of technology roadmaps, from the current state to the future, Fokker Aerostructures, proposes new concepts, selects the promising ones and develops the best into feasible product technology combinations. In the avant-garde of innovative sustainable development Fokker participates in networks of universities, customers, co-developers and suppliers in which skills and knowledge are shared and improved. Exploring the newest is both necessary and, admittedly, quite exciting.