PRETREATING THE CFRP BODY OF A SOLAR CAR

Lighter with plasma

For a faster bonding process, optimized adhesion and to save several kilos in weight, a team of students from KU Leuven University in Belgium pretreated the CFRP components of their new solar racing car with atmospheric pressure plasma prior to bonding.

INÈS A. MELAMIES

With a distance of over 3000 km through the Australian outback and temperatures of well over 40°C, the World Solar Challenge is regarded as the toughest solar car rally in the world. The cars in the ‘Challenger Class’ are eye-catching, and Punch One is no exception: a masterpiece of aerodynamics – smooth, sleek and built for maximum endurance and total energy efficiency (Fig. 1). Working autonomously, the team of 16 students from Leuven University had just 15 months to design and build the single-seater vehicle, which would not only be powered entirely by the sun‘s energy, but would also be ready to face the competition for the most efficient electric vehicle in the world. When the starting pistol fires on October 18, 2015 in Darwin (Fig. 2) the new ‚Punch One’ solar car will be on the start line alongside 47 teams from 25 countries.

The team and their project

Production manager Dokus Soetemans (23) and his colleagues in the Punch Powertrain Solar Team are budding electronic and mechatronic engineers with an average age of 21 years. They all share the same idea: to do something really special with the knowledge they have gained before embarking on their careers. For over ten years Leuven University has offered its masters students the opportunity to do an applied postgraduate course in close cooperation with industry partners. In the short timeframe available, the student teams involved in the Solar Car Project, which takes place every two years, are entirely responsible for every detail of this one and a half million euro project.

Starting with the premise that the new car has to be even more energy efficient than its predecessor, the young designers focused above all on improving the aerodynamics and reducing the overall weight, as well as optimizing the solar cells, electric motor and other components. The former are what gives the solar car its new look: Whilst every

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Fig. 1: Powered only by the sun: The energy-efficient Punch One solar car before heading to the world championship in Australia. A plasma-assisted bonding process reduced the weight of the CFRP bodywork by several kilos.

one of Leuven University's previous models featured a symmetrically arranged cockpit, in Punch One for the first time the driver sits in an asymmetrical position out to the right. This solution reduces aerodynamic resistance by around 30%.

Every gram counts

Less mass means less energy consumption and with a maximum overall weight of 165 kg, Punch One should be 10 kg lighter than its predecessor and a good 25 kg lighter than most of its rivals. Six square meters of the vehicle's surface are covered with 391 ultra-thin silicon solar cells. Yet despite their light weight, they still amount to a total weight of 8 kg. The heaviest part of the car is the solar battery with a specified maximum weight of 21 kg. Here, nothing could be shaved off. So to achieve the desired weight reduction the first job was to replace the two previous motors with a single 5 kW electric motor. The suspension and steering system were also replaced; they are now made mainly from carbon. But the car was still too heavy and the only area left to save weight was the vehicle body itself.

The body

The bodywork, made entirely by the students from mold construction to painting, is a 1.72 meter wide and 4.5 meter long monocoque construction comprising a top and a bottom shell (Fig. 3). These are made from carbon-fiber-reinforced plastic (CFRP), which is 60 percent lighter than steel, around 30 percent lighter than aluminum and yet extremely stable. Using a complex lamination process (vacuum-infused epoxy resin), the students made the shells from prepregs – prefabricated carbon-fiber fabrics with different weave styles impregnated with a synthetic resin matrix. Depending on the requirements profile, multiple layers are built up in different directions, combined with other materials if necessary and then laminated. The

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Fig. 2: Travelling the length of Australia in temperatures of over 40 degrees. The World Solar Challenge is the toughest solar car rally in the world. The cars drive on public roads.

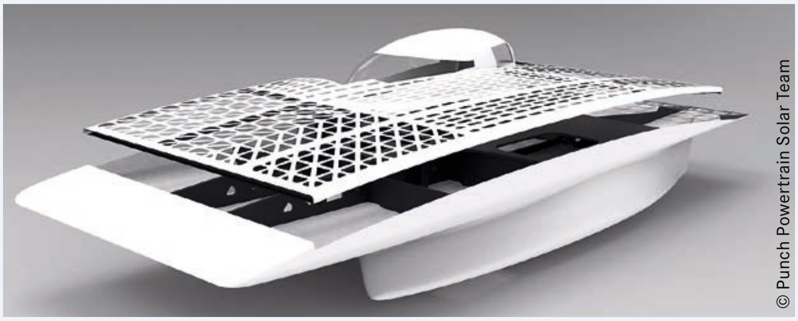

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Fig. 3: Diagram showing the different layers of construction of the solar car.

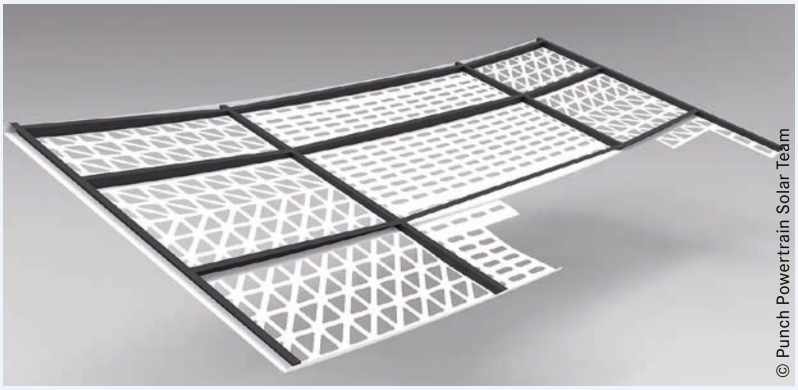

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Fig. 4: Structure of the stiffening ribs in the top shell.

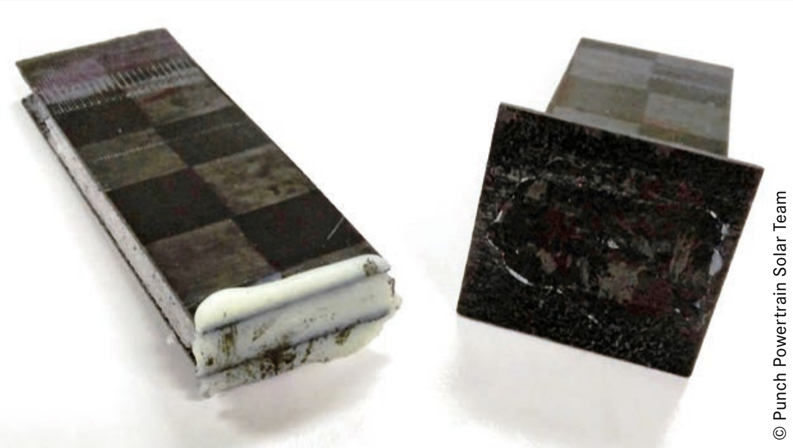
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Fig. 5: Adhesive failure before plasma treatment.

team opted for three types of prepregs: the wafer thin 0.08 mm Textreme (carbon-fiber fabric), an UD fabric (unidirectional) and a 0.23 mm thick twill fabric. A PU rigid foam with high compressive strength was chosen as the core material. Once cured and demolded, plastic shells of this size are strong as far as the material is concerned, but still very unstable due to their light weight, curved shape and large surface area. The top and the bottom shell needed a framework of stiffening ribs to prevent bending and twisting of the substructure (Fig. 4).

Bonding the stiffening ribs

The joining force between the rigid foam ribs encased in Textreme and the bodywork must be strong enough to produce a back pull and counteract any tensile or compressive stresses in the shells in any direction.

With all previous solar cars made by the Leuven students, these static stiffening elements were attached using a lamination process. This involved applying multiple layers and lengths of prepreg strips at each attachment point to ensure that the ribs were firmly bonded to the shell surface after lamination. But this joining method was enormously laborious and time-consuming. In addition, all the extra prepreg strips greatly increased the weight. So the question was whether it would be possible after all to achieve a high-strength bond using adhesives.

The team contacted the company Henkel and obtained permission to test the components with different adhesives. Due to the car's strong vibrations, the adhesive would have to have high elasticity, as well as a short open time to allow the work to be completed quickly. A very fast-curing, 2-component epoxy resin glue (Loctite EA 9466) satisfied these requirements. However, in the first tensile-shear-force tests failure occurred as a result of an adhesive fracture instead of the required cohesive fracture (Fig. 5 and 6). At the fracture point there was no adhesive on the CFRP surface that was to be bonded, despite the fact that this had been pretre-

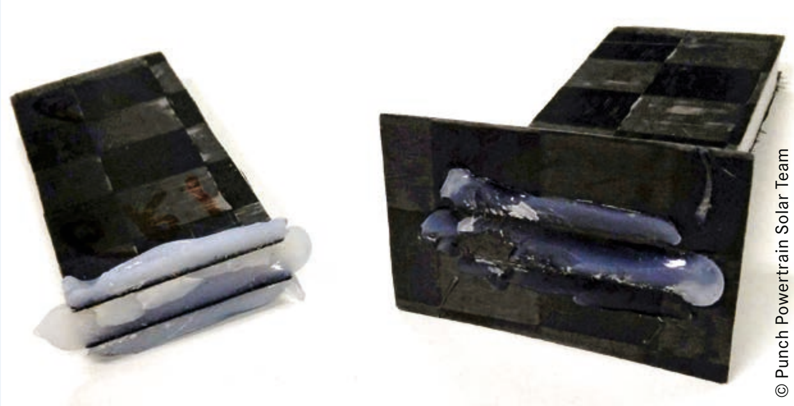
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Fig. 6: Cohesive fracture in the adhesive after plasma treatment.

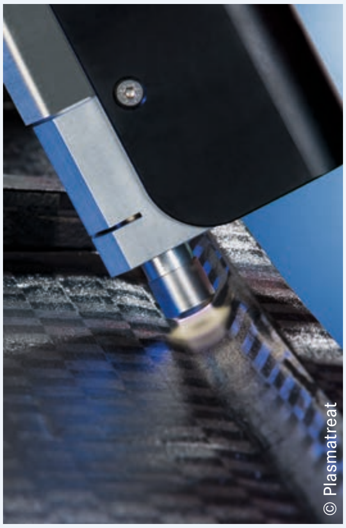
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Fig. 7: Pretreating the lightweight CFRP bodywork of the solar car with Openair plasma. Microfine cleaning and simultaneous activation of the plasma significantly enhance the wettability and the adhesive properties of the plastic surface.

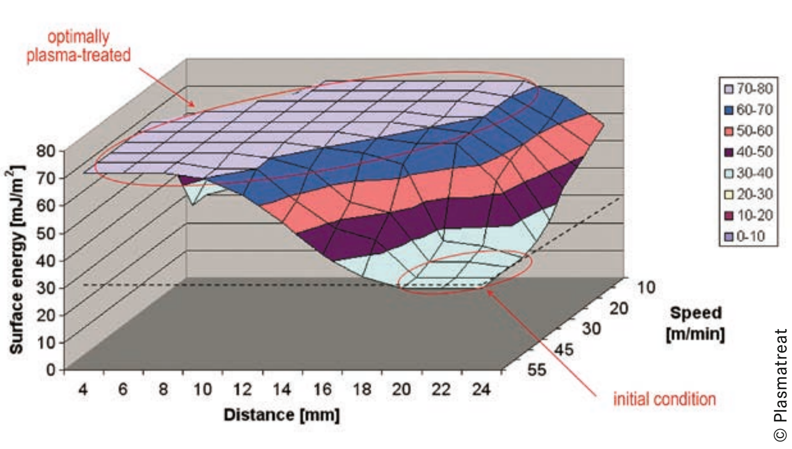

Fig. 8: The diagram shows a non-polar plastic surface which was pretreated with atmospheric pressure plasma as a function of distance and speed. Rendered polar by the treatment, the surface energy rises to >72 mJ/m² (>72 dyne).

Fig. 9: Production manager Dokus Soetemans measures and marks the adhesive surface with millimeter precision.

ated with a special cleaner. Since the surface energy of the material was obviously too low, the adhesive manufacturer recommended pretreating the plastic surface of the ribs with atmospheric pressure plasma (AP plasma). The team took this advice and contacted the Belgian representative of Plasmatreat, which supported the Solar Car Project with its Openair plasma process.

Cleaning and activation with AP plasma

The ‘Openair plasma’ jet technology developed 20 years ago for the pretreatment of surfaces is characterized by potential-free atmospheric plasma. Produced inside plasma nozzles by an intensive, pulsed arc discharge, the plasma is conditioned at the nozzle outlet (Fig. 7). A targeted flow of air along the discharge path separates parts of the plasma and transports them via the nozzle head to the surface of the material being treated, whilst retaining the voltage-carrying parts of the plasma flow inside the nozzle head. The nozzle head also determines the geometry of the plasma jet emitted from the nozzle. The process performs three operations in a single step lasting only a matter of seconds: It simultaneously brings about the microfine cleaning, electrostatic discharging and activation of the plastic surface. This triple action far outweighs the effectiveness of conventional pretreatment systems. The result is homogeneous wettability of the material surface

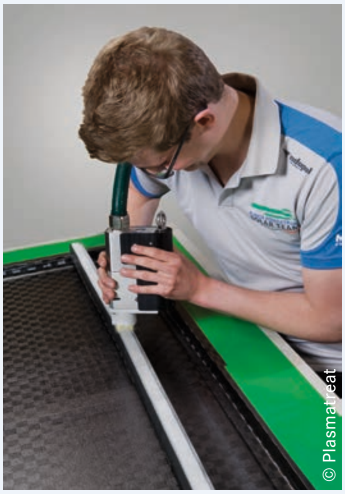

Fig. 10: Openair plasma treatment of the rigid foam rib using a hand-held rotary nozzle.

‘Punch One’ solar car – technical facts

Designer:	Punch Powertrain Solar Team, KU-Leuven
Dimensions:	1.72 m x 4.50 m
Overall weight:	165 kg
Bodywork:	CFRP monocoque, pretreated with Openair plasma (Plasmatreat)
Solar cells:	Silicon cells, 391 units, 6 m² (SunPower)
Battery:	Li-ion 155 V, 5.1 kWh, 36 Ah, 21 kg, range 400-500 km (Panasonic)
Electric motor:	5KW (Mitsuba), reduced to max. 120 km/h (energy efficiency)

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Fig. 11: Immediately after plasma treatment, the rib is bonded with a 2-component epoxy adhesive.

and long-time stable adhesion of the adhesive bond or coating even under challenging load conditions.

The surface is activated through the chemical and physical interaction of the plasma with the substrate. When the AP plasma hits a plastic surface, groups containing oxygen and nitrogen are incorporated into the mainly non-polar polymer matrix. Plasma activation brings about an increase in surface energy, making the substrate polar. Energy-rich radicals, ions, atoms and molecular fragments present in the plasma release their energy at the surface of the material that is being treated and thus initiate chemical reactions which bring about this effect. Some of the functional hydroxyl, carbonyl and carboxyl groups that arise (as well as the oxygen compounds of nitrogen) form very strong chemical bonds with the adhesives and coatings and so help to significantly enhance adhesion.

Convincing test results

Never before had the students experienced a material pretreatment with plasma and they were keen to see the process and its effects. Two different tests had to be performed to verify the effect: one before and one after the bonding process. In the first test the surface energy of the CFRP was determined before and after plasma treatment. Plasmatreat measured the contact angles using the Mobile Surface Analyzer (MSA) from Krüss. The portable instrument applies two parallel drops, then measures the contact angle and calculates the free surface energy in a fully automatic process which lasts no more than a second. The results provide valuable information about the wettability of the surface by aqueous or organic liquids. The findings: The smooth side f the CFRP sample which was to be bonded had a surface energy of 24 mJ/m² (24 dyne) before treatment, but after plasma treatment this figure rose to 74 mJ/m² (74 dyne) (Fig. 8). Ideal conditions for the subsequent adhesive process. The epoxy resin adhesive was then applied again to the pieces of test rib and bonded to the Textreme surface. A repeat of the tensile-shear-strength test provided the proof: The fracture behavior had changed. Instead of the earlier adhesive fracture, this time the desired cohesive fracture was obtained. Construction of the Punch One bodywork could continue.

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Fig. 12: The monocoque outer shell receives its final stiffening rib.

Lighter and faster

Under the direction and supervision of their production manager, three members of the team carried out the plasma treatment and bonded all the stiffening ribs to the two bodywork shells. To make the job easier, Plasmatreat provided a hand-held rotary nozzle normally used for laboratory work or small-scale applications which weighed only 2.5 kg. The process proved to be very straightforward: Whilst one person guided the plasma nozzle across the surfaces to be treated, cleaning them to a microfine level and activating them, the next person followed on behind applying the adhesive (Fig. 9-12). Some pressure to the bonded ribs and off the shell went in the oven for one hour at 90° C to cure the adhesive. While previously it had taken an entire week to laminate the ribs for just the bottom shell, now with the aid of plasma and adhesive the joining process was completed in two days.

Concluding remarks

The Punch Powertrain Solar Team began building Punch One in February and by early June 2015 the solar car was finished. Members of the press were the first to set eyes on the masterpiece. The team and the University were delighted and honored that the car was unveiled by the King of Belgium in person. On 18 October the team will compete for the title of the world's most efficient electric car. The Punch One solar car is in with a good chance. It now weighs exactly 165 kg. ■

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