Recycled Carbon Fibre: A New Approach to Cost Effective Lightweighting
Content

- ELG Carbon Fibre
- Rationale for carbon fibre recycling
- Carbon fibre reclaiming
- Carbon fibre conversion
- Recycled carbon fibre products
- Quality and environment
- Summary
Introduction to HANIEL

More than 250 years of History

Owners
- approx. 680+ shareholders
- 100% family-owned since 1756

Corporate Governance
- Separation of ownership and management

Group Structure
- Four corporate divisions with totally different activities + Investment in METRO:
  - more than 800 companies in majority ownership
  - about 11,500 employees

Corporate Divisions:
- focus on core businesses & market leadership

Franz Haniel, 1779 – 1868
### Introduction to ELG Haniel Group

<table>
<thead>
<tr>
<th>Stainless Steel Scrap</th>
<th>Superalloys Scrap</th>
<th>Other Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycling alloyed scrap</td>
<td>Recycling High-Ni Alloys, Titanium</td>
<td>Ferrochrome, Carbon Fibre, Carbon Scrap, Long Products</td>
</tr>
<tr>
<td><strong>Europe</strong></td>
<td></td>
<td></td>
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<tr>
<td>485 Employees*</td>
<td></td>
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<tr>
<td><strong>Overseas</strong></td>
<td></td>
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<tr>
<td>(incl. US, AUS, Asia)</td>
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<tr>
<td>270 Employees*</td>
<td>110 Employees*</td>
<td>165 Employees*</td>
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</table>

**ELG Haniel GmbH** (Holding Company)

- 23 Employees*

* Total Employees = Ø 1055 Headcount

- Recycling of High Performance Materials (NEW: **Carbon Fibre**)
- 3 business units with the core market segment in stainless steel
- Global market leading company with 45 operational yards worldwide
ELG Carbon Fibre

Turning the Vision ...

2003

Milled Carbon Ltd
- Established as an R&D company
- Pilot scale furnace
- Proof of concept phase

2009

Recycled Carbon Fibre Ltd (RCF)
- Start of commercialisation
- Installation of industrial scale furnace
- First sales to market

2011

ELG Carbon Fibre Ltd
- ELG Haniel GmbH acquired 100% of RCF
- Company was rebranded to

ELG Carbon Fibre Ltd.

- Focus on high volume carbon fibre recovery, conversion to recycled carbon fibre products and QA/QC systems.

... to Commercial Reality
Our Value Chain

The CF reclamation is the HEART of our process, but only one challenge to ‘close the loop’!
Why Recycle?

- **Cost:** recycled carbon fibre products can reduce the cost of lightweight structures and components.

- **Environmental benefits:** significantly reduced global warming potential.

- **Legislation:** increasing onerous legislation regarding the disposal of composite manufacturing and end-of-life waste.

- **Supply chain security:** mitigates against shortages in virgin carbon fibre supply.

![Carbon Fibre Supply and Demand](chart.png)

Recycling of manufacturing waste can help fill the forecast gap between carbon fibre supply and demand.
ELG can produce more than 1,000 tonnes of recycled carbon fibre products each year, using a patented process that results in 95% strength retention and 99% modulus retention.
Fibre Mechanical Properties

- Fibre mechanical properties measured using single filament testing before and after pyrolysis for classification and quality control purposes.

- Reclaimed carbon fibres have similar mechanical properties to the original fibres provided that the reclaiming process is optimised for the type of feedstock being treated.

Based on single filament testing of 1484 fibre batches before and after fibre recovery by pyrolysis.
- Recycled carbon fibres and recycled carbon fibre products offer significant cost advantages.
Environmental Impact

- Recycled carbon fibres have significantly less environmental impact.

Global Warming Potential

Further 36% reduction in energy consumption per kg achieved in 2015

Global warming potential comparison prepared by Fraunhofer UMSICHT based on ELG CF 2014 operational data.
Advantages of recycled carbon fibre

<table>
<thead>
<tr>
<th>Excellent products</th>
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<tbody>
<tr>
<td>- After the fibres go through our process, there is a small loss in Tensile Strength (&lt;4%), and almost no loss in Modulus.</td>
</tr>
<tr>
<td>- We measure the properties of each batch and issue fibre certificates.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Economic gains</th>
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</thead>
<tbody>
<tr>
<td>- Lower-cost, high-value products</td>
</tr>
<tr>
<td>- Stable pricing - not affected by world-wide carbon prices, so we can hold prices stable on a long-term basis.</td>
</tr>
<tr>
<td>- Stable supply - not be affected by any carbon shortages when supply ‘tightens’</td>
</tr>
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<table>
<thead>
<tr>
<th>Social responsibility</th>
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<tr>
<td>- Reduce Carbon Footprint - The recycling process uses &lt; 10% of the energy required to produce virgin carbon fibre.</td>
</tr>
<tr>
<td>- Minimise waste going to landfill / incineration.</td>
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</table>
Recycled Carbon Fibre Products
The product range – Carbiso™

Carbiso™ MF
Carbiso™ CT
Carbiso™ TM
Carbiso™ M

STAPLE CARBON FIBRE

Compounding Industry
Composites Industry
Milled CF

**Carbiso™ MF**

- Standard milled CF
- Average fibre length 80μ or 100μ
- High bulk density
- Typical coefficient of thermal expansion (CTE):
  - Axial: -0.4 x 10^-6mm/mm°C
  - Transverse: 15 x 10^-6mm/mm°C
- Typical thermal conductivity: 5.40 W/(m.K)

Carbiso™ MF has been qualified by an aircraft OEM for additive manufacturing.
Applications for rCF - Milled

Subsea buoyancy

Conductive materials
milled carbon fibre is used to provide electrical conductivity / antistatic properties in polymer compounds and coatings:

• microelectronics industry established standards for safe handling, transport and storage of Integrated Circuits (ICs)
• epoxy antistatic floor coatings
Applications for rCF - Milled

Additive manufacturing — milled carbon fibre is used to make filaments with improved mechanical properties for additive manufacturing (3D printing) processes.

Compounding — milled carbon fibre is used to improve the mechanical properties (mainly stiffness) in polymer compounds for injection moulding.
Chopped CF

**Carbiso™ C**
- Randomly chopped CF
- Standard fibre length distribution: 10-30mm
- Also available in 30-60mm and 60-90mm
- No sizing

**Carbiso™ CT**
- Precisely chopped tow
- Standard fibre length: 6mm or 12mm
- Sizing (<2%)
- Sizing tailored to customer needs
SMC and BMC moulding compounds
used in areas where long fibres cannot
conform to complex geometry or where
there are exacting surface quality
requirements.

Net shape manufacturing
Chopped fibres being used in several
research projects investigating net shape
manufacturing processes--preforming for
resin transfer moulding or stamp forming
applications.
Recycled CF give the same mechanical property enhancement as virgin CF.

10% loading of recycled carbon fibre provides the same mechanical properties as 30% loading of glass fibres:
- 23% density reduction.
- 4% material cost increase.

30% to 45% loadings of recycled carbon fibre provide mechanical properties comparable to magnesium castings and aluminium castings.
With product optimization, 21% weight reduction can be achieved whilst providing the same mechanical performance without redesigning the parts.

- Part cost increase to achieve this weight saving ~2%.
- Over 750,000 tonnes of 30% glass reinforced PA66 compounds used for air inlet manifolds and cam covers each year by the automotive industry => potential for over 150,000 tonnes of weight saving!
Recycled CF products are used to enforce the electrical properties of engineering plastics:

- Milled CF to achieve anything from antistatic to conductivity; targeted properties are subject to CF content
- Chopped tow enables conductivity at low CF content
Carbon Fibre Nonwovens

- Directly in composite manufacturing processes such as liquid compression moulding.
- Used as a raw material for prepreg and SMC products.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>344 MPa</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>36 GPa</td>
</tr>
<tr>
<td>Compression Strength</td>
<td>361 MPa</td>
</tr>
<tr>
<td>ILSS</td>
<td>42 MPa</td>
</tr>
</tbody>
</table>

Typical Laminate Properties
iStream* Carbon

• Conventional stamped steel chassis: Typically hundreds of stamped metal panels.

• iStream hybrid structural composite chassis: Simple, low cost steel tubular members. 14 composite panels.

• iPanesls based on recycled carbon fibre cost approximately €30 each, compared to €300 each for panels made from conventional woven fabric prepreg.

*iStream photos and information courtesy of Gordon Murray Design Ltd.
Structural rCF - SMC

- Sheet moulding compound designed for the rapid production of structural and semi-structural components.
- 12 months shelf life at -18°C.
- 10 days outlife at 20°C.
- 4 minute cure cycle at 155°C.
- 167°C TG after cure.

**SMC Laminate**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Density</td>
<td>1.4 g/cm³</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>370 MPa</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>33.3 GPa</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>650 MPa</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>41.7 GPa</td>
</tr>
<tr>
<td>Compression Strength</td>
<td>264 MPa</td>
</tr>
<tr>
<td>Compression Modulus</td>
<td>33.2 GPa</td>
</tr>
<tr>
<td>ILSS</td>
<td>62 MPa</td>
</tr>
<tr>
<td>TG</td>
<td>150°C</td>
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</table>
Hybrid Nonwovens

- Blends of recycled carbon fibre with polymers such as PP and PPS.
- Used in compression moulding processes for interior and exterior parts in the automotive industry.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>235 MPa</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>29 GPa</td>
</tr>
<tr>
<td>Compression Strength</td>
<td>253 MPa</td>
</tr>
<tr>
<td>Impact Strength</td>
<td>25 kJ/m²</td>
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</table>

Nonwoven Mat → Part Made By Compression Moulding
Opportunities and Barriers

- Milled and chopped recycled carbon fibre products provide a cost effective alternative to virgin fibres in the coatings and compounding industry.

- Nonwoven mats can be used alone or in combination with virgin fibres in the composites manufacturing. It is estimated that 75% of automotive and 90% of electronics applications for carbon fibre could be met with recycled carbon fibre products.

- Recycled carbon fibres are new and relatively unknown, hence there are several barriers that have to be overcome before the materials become widely used:
  - Improved understanding of the fundamental characteristics of recycled carbon fibres.
  - Availability of design and processing data for recycled carbon fibre products.
  - Demonstration of the economic, technical and environmental performance of components made from recycled carbon fibres.
Research and Developments Partners

- California Polytechnic State University (US)
- CSIRO (Aus)
- Deakin University (Aus)
- Dresden University of Technology (DE)
- Imperial College of Science & Technology (UK)
- ITV Denkendorf (DE)
- National Composites Centre (UK)
- RWTH Aachen University (DE)
- University of Bristol (UK)
- University of Nottingham (UK)
- University of Warwick (UK)
Quality Assurance / Quality Control

- Accredited to BS EN9100 (AS9100C)

- Comprehensive quality control procedures throughout the process
  - Classification of incoming feedstock
  - Fibre mechanical property testing through the process
  - Fibre length and fibre length distribution for milled and staple fibre products
  - Flow characteristics of milled fibre
  - Metal detection and separation at key stages of the process
Summary

- Carbon fibre recycling has been established at an industrial scale.
- QA and QC controls implemented to ensure that the requirements of mass production markets can be met.
- An initial range of products is now available for the compounding, coatings and composites manufacturing industries.
- Through a comprehensive R&D programme, ELG CF is now addressing the issues of design data availability and technical / economic performance demonstration that will support widespread application of recycled carbon fibres.