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MACE

Multifunctional Advanced Carbon Aluminium Composite for Electricity Transport

Instrument	**STREP**
Priority area	**Priority 3 – NMP**

Publishable Final Activity Report

Period covered	**January 1st 2004 to December 31st 2006**
Project coordinator	**Neil Wright**
Coordinator organisation	**C-Tech Innovation Ltd., UK**

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1.1.1 Background

Metal Matrix Composites

Metal matrix composites (MMCs) form a new class of materials of great current interest in which a metal bulk is reinforced or filled with other materials to improve mechanical, electrical or thermal properties. They can combine the best features of the component materials to give advanced properties that are unachievable by any alone, and can therefore be tailored for specific applications. For optimum properties an interface of high integrity between the metal and reinforcement is essential. Processing is therefore crucial and subject to much research.

MMC aluminium wires (or EFRA - Endless Fibre Reinforced Aluminium) have major advantages in applications, many of them quite specialised, that demand high strength, low weight, and low thermal expansion. An application with high economic potential is needed to give the impetus to the research which can bring these materials to market. A prime candidate is advanced overhead conductors for electricity distribution.

Overhead conductors contain reinforcing strands in order to achieve long spans and withstand loadings from wind and ice. EFRA wires using ceramic fibre have low thermal expansion and high strength, and are being developed as an alternative to the commonly used steel reinforcement. Carbon fibre, however, offers far better properties even than ceramic. It is stronger, lighter, 90% cheaper, electrically conductive and has lower thermal expansion, reducing sag. Carbon EFRA wire is not commercially available, however, because it is extremely difficult to achieve a good interface between the carbon and aluminium. Much research is required.

The problem – overhead conductors

Electrical utilities are under pressure to extend the network for increased demand and implementation of European policy of increasing cross-border trading, but there is increasing resistance to the environmental impact of overhead lines. Underground cables are more acceptable, but are expensive (>10 times dearer), slow to install and subject to complex legal procedures. Reliance on them would hinder Europe's competitiveness. Existing lines would overheat if they carried more current and would require higher towers to accommodate the increased sag. This is expensive and environmentally unacceptable. High temperature conductors are emerging, but using expensive ceramic fibre, are up to 4 times dearer and still need environmentally damaging taller towers to accommodate the sag which would arise from a worthwhile current increase.

The solution

is to develop advanced conductors incorporating carbon EFRA wire. The extremely low thermal expansion reduces sag by an order of magnitude, allowing higher current. This and the high strength/weight ratio permit use of smaller towers and reduce the need for new lines. The new conductor would have lower losses by at least 3%, and a current capacity increased by 80%. (Distribution losses in Europe are about 200TWh/yr, releasing over 60M tonnes of CO_2).

The technical challenges

Carbon EFRA wire production is prevented by the fibre's resistance to "wetting" by molten aluminium, and by interfacial reactions. Previous research showed the potential of flux-assisted infiltration, and plasma pre-treatment to overcome this, and a "rounding" process was conceived to correct the flatness caused by the ribbon-like fibre bundle and by the pulleys in the flux infiltration. Both infiltration and shaping needed extensive further research before they would be ready to move beyond the laboratory. Novel liquid metal electromagnetic control was investigated to facilitate the necessary continuity between the two. It was a major challenge to develop all of these and to combine them into a continuous process with real industrial prospects. A further technical challenge was to wind the highly stiff EFRA wire into a conductor. Research into special conductor designs and manufacturing methods was therefore required.

1.1.2 Overall Project Objectives

- Overcome the interfacial problems between carbon and molten aluminium which prevent production of the wire
- Facilitate its continuous production.
- Research its use in a conductor of: high ampacity; high mechanical strength, low losses; low sag; long span.
- Devise advanced conductor stranding techniques
- Facilitate expansion of the overhead electricity network with reduced environmental impact through fewer new lines (~500km less per year) and lower towers.
- Promote exploitation of the composite in a wide range of applications (e.g. robotics, aerospace).

1.1.3 Detailed Project Objectives

- Optimise plasma flux infiltration method for carbon EFRA wire manufacture.
- Optimise plasma pre-treatment method for carbon EFRA wire manufacture.
- Study the interface, minimise unwanted products, optimise the wire properties.
- Develop a new fibre-rounding technique, with the targets of zero carbon exposed at surface, and a roundness of maximum $\pm$10%.
- Devise and demonstrate the components of an integrated process, which can produce *for the first time*, continuous lengths.
- Develop methods for stranding the highly stiff EFRA wire into conductor forms.
- Produce a practical conductor sample, at least 30m long. This should give an increase in current carrying capacity of 80%.
- Assess the feasibility and costs of manufacture. It was anticipated that the new conductor's advantages could justify a price premium of up to three times the cost of a conventional conductor.
- Establish operational data (e.g. losses, corrosion resistance) for short sections.
- Demonstrate the potential for a new generation conductor establish operational data for short sections of networks.

1.2 Contractors Involved

	Participant	Short name	Country
1	C-tech Innovation Ltd	C-Tech	UK
2	SAG Energieversorgungslösungen GmbH	SAG EL	Germany
3	ARC Seibersdorf GmbH	ARC	Austria
4	Association pour la Recherche et le Développement des Méthodes et Processus Industriels	Armines	France
5	Université Catholique de Louvain	UCL	Belgium
6	Kema Nederland B.V.	KEMA	The Netherlands
7	Lumpi-Berndorf Draht und Seilwerk GmbH	Lumpi-Berndorf	Austria
8	Lamifil NV	Lamifil	Belgium

C-Tech is an industrial research and technology development consultancy designated as an SME. It has 40 years' experience of developing products and processes for the industrial, commercial, energy and domestic markets. The company has participated in, and coordinated a large number of European and UK government funded research projects in the last 15 years. C-Tech has considerable experience in atmospheric pressure plasmas. Following development of fibre handling techniques, the company's plasma system has been demonstrated to be capable of successful surface modifications to these materials.

SAG is a one of the leading service providers in HV transmission lines and substations and has participated significantly in the development and security of electrical transmission and distribution networks. It plans, erects and services the technical infrastructure for power and media both in Europe and worldwide. The Research and Technology Center of SAG GmbH is a non-affiliated and accredited testing facility for the examination of components, assemblies and complex systems for power supply: Key points of testing are the operative capabilities and safety of systems and the interaction of individual components and systems.

ARC is Austria's largest non-university RT&D establishment and has many years' experience of transferring research results to practical applications in Austria and abroad. ARC operates as an ESA Test House for metallic materials and is highly experienced in EC-funded projects. The Engineering Division has specific expertise in materials' development and characterisation including Metal Matrix Composites. In addition, it is skilled in processing MMC's.

Armines is a non profit research foundation associated with Ecole des Mines de Paris and other technical schools with a total work force of 500. Centre des Matériaux was founded by SNECMA and by Ecole des Mines in 1967 for joint collaboration between industry and academia, and has participated in many EC projects. Armines has long experience in MMC processing, characterisation and modelling, and expertise in chemically activated continuous infiltration processing.

UCL, through its IMAP division (Unité d'ingénierie des matériaux et des procédés), has research activities in the study of processing, testing, characterisation and modelling of advanced metallic and ceramic materials. IMAP is expert in the field of interface characterisation and property assessment of advanced MMC's, and has squeeze casting facilities. The division participated in many European-funded projects.

KEMA is an independent consulting organisation of over 1600 people, providing consultancy, testing, research and quality management services within the fields of generation, transmission, and distribution of electricity. With company headquarters in Arnhem, the Netherlands, KEMA also has offices in seventeen other countries. KEMA enjoys an international reputation for reliability, integrity and expertise in the above and has extensive experience in conducting projects on a national and international level.

Lumpi-Berndorf is a private company with more than 150 years of experience in the metal industry and diversified activities in different areas. The Technology group of Berndorf encompasses activities in various areas, with the production of special wires and conductors being the most prominent. Lumpi-Berndorf is the only manufacturer of high temperature conductors in Europe and the only company in the world producing coated conductors. Another daughter company is a leading supplier of environmental engineering and equipment such as air and gas cleaning and drying systems, solvent recovery, adsorption technology etc.

Lamifil is part of the Lamitref metals group, which is one of the few independent suppliers to Europe's major cable manufacturers. They have 70 years of experience in the manufacture of copper and aluminium rods, wires, bunches, strands and overhead conductors. Lamifil has a number of strong performers in its aluminium product range for use in electricity distribution, many supplied to electricity distribution companies in Western Europe. Lamifil's extra-high conductivity technology has enabled it to become a leading producer of alloy overhead resistant aluminium alloy conductors, and the company markets its heli-formed line products world-wide. Lamifil is one of the few European wire producers that is experienced in liquid metal technology.

1.3 Work Performed

The sequence of operations that is necessary to produce an EFRA wire reinforced conductor contains technical challenges at a number of stages. The project devoted specific workpackages to meeting each of these.

- Research flux chemistry, plasma pre-treatment and wire shaping to allow infiltration of carbon fibre by molten aluminium for optimum composite properties.
- Develop liquid metal control to facilitate combination of these technologies in a continuous route.
- Design an advanced conductor incorporating EFRA wire
- Develop special stranding techniques to cope with the highly stiff EFRA wire and produce test lengths of conductor.
- Compile a technico-economic assessment including exploitation prospects in wider applications.
- All of the above were supported by continuing activities in materials assessment and analysis, involving some new or specialised techniques.

1.3.1 Flux-Assisted Infiltration

Carbon fibre is supplied in bundles, or "tows", of typically 12,000 fibres of 6 microns diameter. The poor wettability of carbon fibre by molten aluminium leads to poor transfer of forces between the two materials in the composite. Fluxes can be used to overcome this, but generation of brittle intermetallic compounds can also degrade the interface, further reducing the performance of the EFRA wire.

Armines investigated the use of special fluxes to overcome these difficulties, in a specially constructed pilot laboratory rig that allowed continuous production of infiltrated wire. Carbon fibre is fed from up to 3 spools, through a thermal desizer that removes the protective polymer coating, into an aqueous flux bath at controlled temperature, then into the molten aluminium bath. On exit, the wire cools and is wound onto a take-up spool. Since the arrangement involves entry and exit from above, guide pulleys are submerged in the aluminium bath. Armines' experiments involved: selection of fluxes; desizing temperature; and operating conditions (speed, temperature). In addition, they investigated materials and designs for the pulleys in order to afford satisfactory service in their harsh environment. The technology was transferred to ARC for incorporation in the continuous process that they were developing. In parallel, Armines continued to investigate the use of dies for forming the composite wire into a round section, as an alternative to the originally conceived method that utilised profiled guide pulleys.

1.3.2 Plasma Pre-Treatment

A plasma is an ionised gas, produced either in vacuum or, if high strength electric fields are used, at atmospheric pressure. Plasma processes take many forms, but the vacuum type, in particular, is very useful for surface processing. C-Tech developed a plasma that has these characteristics, but, conveniently, is generated at atmospheric pressure. This was included in the programme to desize the fibre non-thermally (potentially less damaging) and to treat the surface of the fibre to improve adhesion between the aluminium matrix. The neutral plasma gas can itself activate the surface, but in addition, it also provides a chemically reactive gaseous medium that can be used to deposit a coating. The programme included investigation of coating materials that not only protect the fibre surface from the aggressive molten aluminium, but also have mutual compatibility with both the carbon fibre and the aluminium, thereby improving the interface, and hence, potentially, the mechanical properties.

1.3.3 Control of Molten Aluminium

The MACE project includes the establishment of an integrated processing route for EFRA composite wire as an important deliverable. One impediment to producing round wires is the necessity to use pulleys submerged in the aluminium melt in order to achieve entry and exit of the fibre through the top surface. The original MACE concept aimed to obviate these pulleys by permitting entry and exit through the side walls of the bath by using electromagnetic forces to prevent the molten aluminium from escaping through the apertures. C-Tech devised an arrangement that maximised this force by applying a parallel field across the aperture while imposing orthogonally directed current in the melt immediately behind the aperture. The principles were tested using solid pieces of aluminium, which facilitated both easy application of current and measurement of force by an adapted laboratory balance. The effective area over which the force was applied, combined with the force enabled the head of liquid aluminium that could be supported to be calculated. Parallel experiments were conducted on passing of current through the molten aluminium via electrodes.

1.3.4 Wire Rounding and Process Integration

It is essential, that the infiltrated wire is of round shape so that it can be stranded and wound into a conductor. The original flux infiltration method has a natural tendency to produce, at best, ellipsoid wires, for two main reasons: firstly, the carbon fibre tow is originally flat and this cannot be corrected during infiltration; secondly, the current method uses pulleys submerged in the molten aluminium, which also tend to flatten the composite wire's section. A key innovation in MACE, conceived by ARC, is a rounding method that forms the wire into a circular section. This utilises sets of shaped rollers, impinging on the wire from various angles. Experience suggested that this would need to be done before the wire has had time to cool after leaving the infiltration bath. This proximity of the two processes, infiltration and rounding, necessitates their combination in a single integrated rig that has continuous production of round wire as a goal. Following early development, Armines transferred the necessary flux infiltration technology to ARC, as the basis for their development of the rounding system. This permitted the preliminary work on the rounding concept. After that, they were to proceed to incorporation of both techniques in an integrated rig.

1.3.5 Property Assessment

Collectively, the MACE partnership provided a wide range of analytical skills for assessing the various relevant properties and capabilities of the composite wire produced in the research. UCL coordinated these activities, which underpinned the development of the composite wire. Broadly, the measurements covered: analysis of the plasma coatings; composite properties, such as fibre volume fraction and porosity, mechanical properties; electrical properties; and corrosion performance. As well as metallographic examinations, UCL also applied their own novel methods for measuring porosity and density, and have facilities for surface analysis. Lamifil have equipment for fatigue tests in bending and torsion mode, which are very relevant to the stranding of the conductor. KEMA developed a dye penetrant technique for analysis of longitudinal porosity, contributed some metallographic examination of the coatings, and measured electrical properties. SAG carried out electrical tests and elongation tests. Armines also have metallographic facilities, and tensile test equipment. The group was well covered for corrosion tests, with both KEMA and SAG having salt fog test equipment.

1.3.6 Conductor Design, Winding and Testing

The carbon EFRA wire is much stiffer and more fragile than conventional reinforcements, and presents new handling problems. This has major impacts on the manufacturing process. To maintain economy of manufacture, however, it is desirable to utilise existing equipment as far as possible. Lamifil and Lumpi-Berndorf are major conductor manufacturers, and led the work on this. They develop new stranding methods for the EFRA wires generated, and defined manufacturing parameters. These same special properties also raise quite severe problems in assembling the conductor, both in presenting the wire from its spools, and in stranding it into the conductor. These issues, as well as testing of the conductor, were addressed. Test of conductors followed as appropriate.

It is also a challenge to design a conductor which fully exploits the advanced properties of the new material, and KEMA developed a model for predicting the performance of the conductor, in terms of sag, in particular, and assessing its advantages. The aim was that this would be a tool that could be used to maximise the exploitation of the benefits which the new conductor material offers..

1.3.7 Techno-Economic Assessment

The technico-economic evaluation is a key output, since it determines the prospects for the new technology, and allows quantitative assessment of the benefits. It also offers realistic expectations for exploitation of the outcome, with timescales. Led by KEMA, a projected cost assessment was undertaken to determine the market potential of the ACCR conductor. In addition, social and environmental impact were considered.

1.4 End Results

1.4.1 Flux- Assisted Infiltration

Armines established a flux that satisfactorily achieved the required wetting of the carbon fibres by the molten aluminium and generated considerable understanding of the process. They established optimum operating conditions, including desizing temperature. This was evident in the production of wires that had the required combination of low porosity, high fibre fraction, high tensile strength and modulus. The problem of intermetallic deposits in the fibre/matrix interface was eliminated.

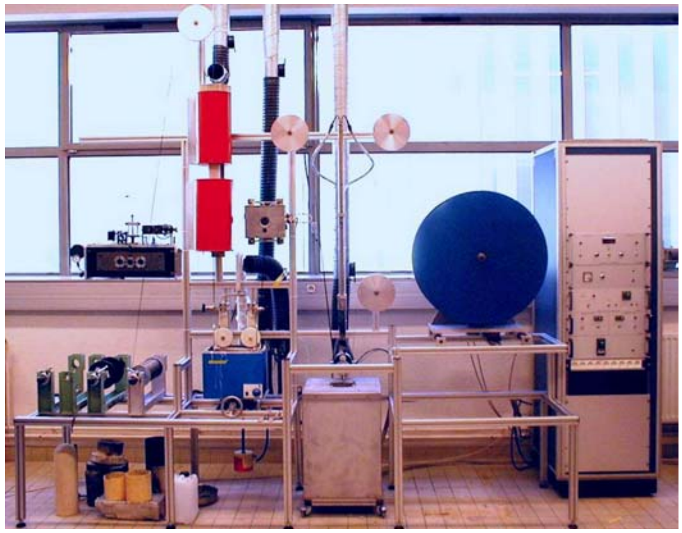

Figure 1. Flux infiltration apparatus

Armines also obtained good roundness of section, using a die at the exit of the aluminium bath. After experimenting with various designs and diameters, they met the target value at low wire diameters. At larger diameters, which are more practical for conductor stranding, roundness was not quite as good, and less consistent over the length. However, it was not an objective of this part of the work to achieve roundness, since the wire is to receive more intense shaping in the continuous process, to which this flux infiltration work was providing support.

1.4.2 Plasma Pretreatment

C-Tech carried out the initial trials on carbon discs in order to allow convenient XPS analysis of the deposited material by UCL. Various combinations of precursors and plasma conditions (power, flow rate, carrier gas, etc) were tested. Work centred on establishing reducing conditions, rather than the oxidising chemistry that is readily generated in a plasma. The other main challenge was to produce coatings that are both adherent and cohesive. A range of conditions was found that produced coatings of acceptable physical properties. Confirmation of the precise chemical nature by XPS analysis was not practical due to the lengthy and involved procedure. Ultimately, the mechanical performance of composites incorporating the plasma-treated fibres is the best way to accurately assess the benefits of the process. C-Tech therefore modified the plasma for continuous treatment of carbon fibre tows from spool to spool. They then experimented with various glass constructions to expose the running fibres to activated gases emerging from the plasma unit in a controlled manner, and without unwanted ingress of oxygen into the treatment zone. Several long lengths of treated fibre tows were distributed to ARC and Armines for processing into composite wire, and subsequent mechanical testing. Further samples were sent to UCL, who formed composite wires in a less representative, but more convenient, “squeeze casting” process. This did not give conclusive results, however.

1.4.3 Control of Molten Aluminium

Various combinations of permanent magnets or electromagnets with application of either AC or DC current to the aluminium test piece were tested. The aim was to maximise the pressure that could be applied, and hence the head of aluminium that could be supported as determined by calculation. Additional "passive" systems, in which current was not separately applied to the molten aluminium, were also tested. One of these, using a multi-layer coil and a ferrite core, proved to generate the highest force per unit area, demonstrated the capability to support a head of over 50mm. This is more than sufficient to allow the implementation of a horizontal process, with the fibre entering and exiting through the side walls of the aluminium bath. This would have great benefits in removing the need for pulleys, and their tendency to flatten the wire. However, the electromagnetic force also tends to wipe the aluminium from the fibre as it emerges from the melt, which is counter to the needs for a good composite wire. Although the flux method is adequate for ensuring wetting of the fibre by molten aluminium in normal circumstances, the effect is not sufficiently strong to counteract this "wiping" action. During the first year of the project both flux infiltration and rounding made promising progress, suggesting that pulleys could still be used without substantial detrimental effect. Further work on electromagnetic control was therefore halted.

1.4.4 Wire Rounding and Process Integration

ARC built an experimental version of an integrated rig that incorporated a desizing-furnace, flux infiltration bath, furnace for drying and a bath of molten aluminium, which is immediately followed by a set of rollers designed to impose a round cross-section on the wire. They experimented with several key parameters in optimising the performance of the rounding equipment, including: speed and temperature control; profile and disposition of the rollers; material of the rollers; and applied roller pressure. They developed a temperature measurement system based on pyrometry, which is crucial to the operation of the system. ARC established that it is essential that the wire is rounded while it is still hot enough to be malleable, requiring very close proximity to the flux infiltration bath. Unfortunately, this is extremely difficult to achieve within the geometry of the continuous integrated process, and the system failed to produce the desired rounding effect in spite of trying many variations on the roller arrangement.

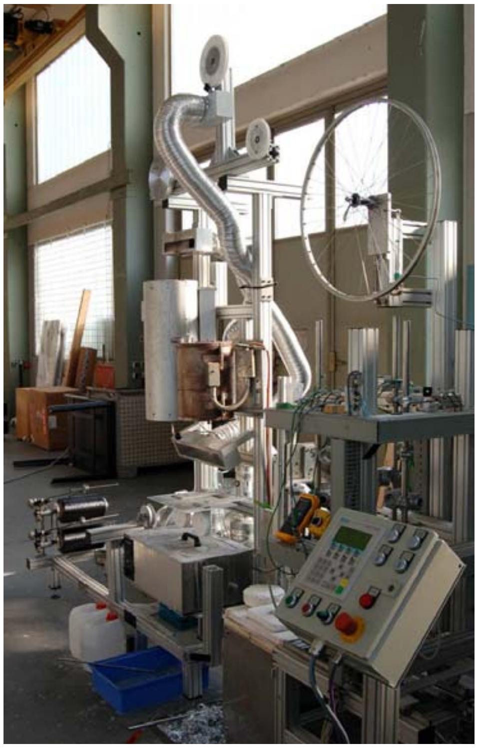

Figure 2. Integrated Process Rig

ARC therefore carried out further, unscheduled work, using dies as an alternative rounding method. The dies were positioned at the exit of the aluminium bath, partly immersed in the melt. This work was done in close alliance with Armines. Some good results were obtained, producing small diameter wires of very good roundness, without porosity, which gave improved mechanical properties. Continuous lengths of up to 350 metres were produced. However, it proved difficult to produce consistently round wires at larger diameters, particularly in the face of some persistent problems were encountered. These included: a lack of aluminium at the surface of the wire; rapid wear of the die; and a tendency for the die to become blocked after some time of operation. Alternative materials could be used to reduce wear of the die. It was concluded, however, that the plugging resulted from accumulation of fibre fragments that tend to be generated at any pulley that follows the desizing process. Given that the fibre must be transported through the bath and rewound on to a spool at the end of the process, it is difficult to avoid using some pulleys. Nevertheless, ARC were able to produce 500m of wire for the conductor manufacturers to test, by removing the die altogether. Although this meant that the wire was outside of the target specification for roundness, it was adequate to allow stranding tests to proceed. The work generated much useful information on necessary parameters and control for an integrated flux infiltration and conductor rounding process.

1.4.5 Property Assessment

The aim of the plasma treatment was to desize the fibres and to produce a coherent coating that is elemental, rather than an oxide, and which is mutually compatible with both carbon and aluminium. XPS analysis of disc samples by UCL, and on fibre samples by KEMA confirmed a reasonable amount of the required element deposited, but gave little evidence of its form, a variety of compounds being identified. SEM analysis and pyrolysis of coated fibres indicated coherent coatings of about 1 μm thickness.

UCL determined density, fibre volume fraction and open porosity of the EFRA wire using an Archimedes method, returning values typically of 2.2 g/cm³, 60% and 4% respectively. The dilatometric properties of the wires were well within the target. KEMA developed a dissolution technique in conjunction with a pycnometer to determine both weight and volume fractions. However, the method was only reliable at relatively high pore contents, although it would be improved if the densities were very accurately known. KEMA also worked on developing a dye penetrant test for establishing the composite's quality. Samples were also examined by SEM, by UCL and by Armines, who also conducted WDS X-ray microanalysis (EPMA). The sections show that good roundness can be imposed on the wire by the die. The method can also reveal the degree of intermetallics, which are detrimental to performance.

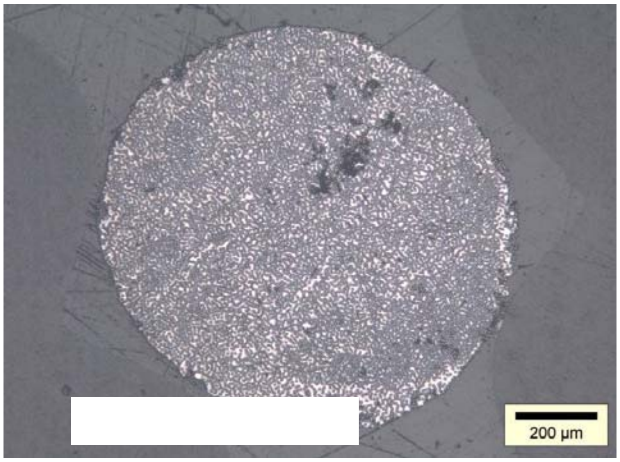

Figure 3. Section of rounded wire

KEMA adapted a 3D X-ray tomography method, more usually used for non-destructive testing and medical applications, for assessment of the composite wire. It proved capable of providing exact information on position, distribution and quantity of carbon fibres, voids and aluminium, as well as on fibre behaviour (breakdown) after functionality tests. At the moment tomography is a stand alone method, but it could easily be adapted for on-line quality control. Because of the complex structure of these composite wires, compared to conventional ones, this capability could have a major impact in generating the confidence that will eventually be needed to facilitate their introduction and acceptance.

SAG, Lamifil and UCL measured tensile strength and Young's Modulus of the composite wires, using special techniques to allow for their brittleness. Young's modulus was 100GPa. UCL also tested some samples after heat treatment, which should strengthen the Aluminium matrix. In the best case, strength at rupture was of 804 MPa, (elongation 0.76%) which increased to 909 MPa (elongation 0.83%).after heat treatment. These partners calculated the Young's Modulus using tensile methods, and, for wires that were adequately round, using a resonant frequency method. Values ranged from 100GPa to 133GPa. Theoretical Young's Modulus of these wires is between 148 and 159 GPa. Both parameters depend on the volume fraction of the C fibres. This shows that about 20 to 30% of the fibres are not contributing, due to factors such as porosity, fibre misalignment and presence of impurities. This also means that the fibres' maximum stress is around 1700 MPa, which is the best result expected from supporting work. Fractography shows pull out of the fibres when the interfaces are weak enough and almost no pull out when hard and brittle reaction products are present at the interface between C fibres and Al matrix.

Lamifil performed torsion tests, static bending tests and dynamic bending/torsion tests, which are all directly relevant to conductor winding. Torsion levels were up to 0.4 rad/mm at total breakage. In bending tests, the calculated bending strain at breakage ranged from 0.4% to 0.7%, equivalent to bending radii from 240mm to 150mm. In the dynamic bending/torsion tests, a bend is applied to the wire, which is the rotated about its own axis, so that the bending stress rotates around the fibre. A bending radius of 400mm led to a break after 21,000 rotations, which is quite low, while an impracticably large radius survived 2,700,000 rotations without any breakage.

Creep tests on single EFRA wires were performed by SAG in order to determine the long term stability under the influence of tensile load and temperature, using aluminium wire as a reference. Creep can increase the initial sag in overhead transmission lines. The wires were cycled repeatedly between 80 and 150°C at about 20% of breaking load, which corresponds to the "every day stress" load level of AAAC or ACSR conductors. The first 100 hrs is dominated by material creep which is only about 75% of that for aluminium wire, and then stabiises. For temperature cycling the EFRA wire creep is similar to the aluminium wire, so these effects have to be considered for practical use of EFRA wires in conductors. Coefficient of thermal expansion was measured at an average of 5.6 ppm/°C.

SAG and Lamifil measured the electrical resistivity of the wire to be about 85nΩm. Repeatability was good and the value is within expectations. KEMA have developed tests to assess corrosion performance, which is promoted electrolytically due to the difference in electropotential of aluminium and carbon. The method is based on a salt spray exposure to ASTM standards, followed by visual inspection. Some corrosion occurred, but the wire samples had significant carbon exposed at the surface. The situation would be improved by modifying the EFRA wire production process to give an aluminium-rich surface. In any case the conductor would be protected in service by grease, which remains in the conductor even at elevated temperatures.

These tasks have produced a comprehensive range of measurements that proved crucial in assessing the practical prospects for the EFRA wire. Important new techniques for quality assessment for these specialised materials were established, including highly valuable on-line monitoring for voids. The mechanical measurements show that at present the EFRA wire has achieved the required properties, which would have implications for both the winding of the conductors and for performance in service. Bending stress, is the most important parameter, and these measurements dictate the necessary modifications to the winding equipment.

1.4.6 Conductor Design, Winding and Testing

KEMA developed a model for conductor performance. A key output is the prediction of sag, which is a prime parameter affecting application and installation. They added an allowance for pre-stress as a conductor production feature, and investigated the sag of the conductor as a function of temperature for a range of variables including fibre volume fraction of the wire, pre-tension, and various mechanical parameters.

The model showed that as the temperature increases, it reaches a point at which the modulus of the core will become equal to that of the carbon fibre. For fibre volume fractions (V_f) greater than 40%, the effect on sag is relatively modest at lower temperature, but as temperature increases the higher volume fraction starts to reduce sag significantly. For example, at 200°C a V_f of 75% gives a sag that is over 20% less than for a V_f of 40%. Initial tension has a much stronger effect. As well as flattening the response of sag to temperature, it introduces a marked resistance to sag. The New EFRA wire has mechanical properties that lend it well to application of this technique.

This model is a valuable tool that permits an assessment of the capabilities of conductors incorporating certain material properties, such as modulus, and can be used to evaluate the impact of the properties of the EFRA wire produced in the project. The program was also developed to include twist and different core materials. It has the potential, also, to include indication of a warning if the modelled parameters are not realisable in practice due to stranding constraints.

Lamifil measured mechanical properties of the EFRA wire in order to assess the implications for conductor manufacture, regarding feasibility of existing machines, which is preferred in order to control costs. They calculated theoretical torsional strain in each of the five layers of the core for a range of assumed wire strains at various wire diameters, then carried out practical tests, in which a core of seven strands was made. Lay length was continuously reduced from infinity until breakage occurred. This happened at a lay length of 250mm. By interpolation from the theoretical results it was determined that the elongation at this point was 0.12%. The torsion was 0.025 rads/mm. Values closer to 0.05% and 0.016 would be preferred for winding this material, it being advisable to restrict lay lengths to about 10% of the maximum elongation.

Lamifil also assessed accommodation of the EFRA wire on the bobbins and of the wound core drums in the winding processes. Minimum lay length is dictated by the torsional strain experienced by the wire, while maximum lay length is dictated by the elongation from winding on to the drum. Even though the composite is far from optimised, the tests showed that existing equipment can be used, provided some modifications are made.

Lamifil and Lumpi-Berndorf carried out stranding tests on the samples produced in the integrated rig. Lamifil worked on a total length of 348m, received in two separate freely wound coils of 165m and 183m. Each of these had breaks, however, in spite of careful packaging, which caused some difficulties in transferring them to the bobbins for the stranding tests. A bobbin diameter of 570mm was chosen in order to provide a significant increase over the diameter of the received coils. Two bobbins were made: one for each of the coils. Although no stranding tests were possible because of insufficient continuous lengths, a small conductor sample was nevertheless made from seven lengths of EFRA wire and twelve lengths of aluminium of 1.6mm diameter. Strength and resistance of the conductor were measured. In spite of not being optimised, this conductor's performance was close to that of an AL4 Advanced Aluminium Alloy Conductor (AAAC) comprising seven strands of diameter 2.33mm, and would be expected to exceed it's performance at temperatures over 90°C. These measured parameters therefore indicate that if consistency can be achieved, its performance could be competitive, particularly at higher temperatures.

Figure 4.

Sample conductor incorporating EFRA wire core.

Lumpi-Berndorf worked mainly with wires that had not been rounded, since the integrated unit could manufcture almost unlimited lengths (up to 500m) of EFRA wire if the rounding die was omitted. A small quantity of rounded wire was also used. With these they investigated the manufacture of conductors of different constructions: EFRA wires only; and mixed designs also incorporating (ACS). Lumpi-Berndorf Based extensively modified their machines to allow for the high stiffness and brittleness of the EFRA wire. On the rewinding equipment these included adjustments for handling loose coils (the EFRA wires were produced this way), and increasing the bobbin core diameter (winding radius). On the stranding equipment and pre-forming they adjusted the rolls and guidance for larger diameters and radius, and introduced designs and materials to make the transport of the wires as gentle as possible.

The lengths of lay were selected to be as large as possible, allowing for the fact that some samples were too short. For the mixed constructions, an ACS wire with the same diameter as the fibre wire was used. Drawing-off tension was lower than desired since it was difficult to provide adequate wire support. The ACS core provided some guidance for the unround EFRA wire, but it was still difficult to wind the conductor, while breakages made it harder still. Lumpi-Berndorf were able to produce conductor samples with this non-optimised wire, however, but it was only possible at low speeds and with manual intervention.

Figure 5. Stranding of the EFRA wire.

Both the theoretical and test results from stranding and winding indicate the potential of the EFRA wire as an advanced conductor core material. The non-optimised wire caused difficulties due to its non-round nature and fragility, but the project has indicated that if the EFRA wire can be improved then a competitive conductor would be possible. For the future, the project identified various enhancements that could improve the mechanical properties of the composite wire, but the crucial element is to find a means of ensuring consistent roundness without generating breakages.

1.4.7 Techno-Economic Assessment

The technico-economic assessment of advanced high capacity overhead conductor lines is an important output of MACE, and was led by KEMA. European Asset Managers and high voltages experts of the grids were interviewed about their demands for advanced conductors. The main issues discussed were cost factors, the expected development of their grid and a review of the capacity increase. Some countries have specific topics because of the laws and rules in their regions.

The starting point was to estimate the expected capacity within a period of 30 - 40 years. The main issues for developing new lines, in decreasing importance are:

- high reliability and capacity
- low budget
- low sag
- less joule losses
- low electromagnetic field.

However, the first precondition is that the mechanical strength for the new lines is satisfactorily reliable. The quality of the grid is supervised by governments, which should give security and reliability. In some countries, such as the Netherlands, the government is also the owner of the grid, but this is not always the case in Europe.

The European grid is expected to grow by 3.9% per year. Steel core conductors have limited properties in many applications. The plan is to upgrade the existing routes by replacing the old conductors by advanced conductors with 1.5 – 2 times the capacity. In the Netherlands alone, 15 power plants will be commissioned in the next 5 years. In other countries there is also increasing economic activity, which will lead to a power boost with consequent demand for the replacement of conventional conductors with advanced ones. Europe seems to be correcting a backlog in power production, while another important issue for European policy is the increase of interconnecting capacity on the borders of the states. The interviewed asset managers have wide interest in the advanced conductors and new developments. As a consequence of the upcoming power boost in Europe, the grid will be different and heavily loaded. New routes will be very seldom applied, probably only with the aim of having more reliability and interconnection between countries.

An advanced conductor such as MACE has a good opportunity for the replacement market if the price is less than twice that of the steel core conductor. There is a need for pilot projects because a first application is always considered as experimental. It is highly desirable that there is a European competitor in the field for developing advanced conductors.

Lumpi-Berndor and Lamifil provide a manufacturer's perspective, confirming that the present situation in high-voltage transmission in Europe requires rapid action. Due to the changes in power flow in the network, which are caused by liberalisation, the closing of old power stations and the feed-in of wind mills, new solutions must be realised very quickly for the electrical uprating of existing lines to avoid further "black-outs". The market situation for EFRA wires is therfore in the near to mid-term future. A technical solution would be extremely helpful for all European users, particularly in the light of the existing competition from the USA.

2 Dissemination and Use

ARC Seibersdorf presented a paper at the conference ICMEN and "The Coatings", hold in Kassandra-Chalkidiki, Greece, 5-7 October 2005. The paper described the mechanical rounding apparatus as built for WP5. UCL are planning a scientific publication at some point in the future.

The MACE project website can be found at: http:/www.mace-conductor.com .It contains basic information about the background to the project, and links to the websites of each of the participants.

The consortium approached the MMC-ASSESS network, whose activities have continued beyond its initial funded period, although greatly diminished. This network contains leading experts on metal matrix composites, who are well known to the consortium. It is anticipated that this organisation, or at least its former members, could assist in pursuing exploitation outside of the immediate application. Dialogue has continued with a carbon fibre manufacturer, and with a wire coating company, both of whom are interested in the exploitation stage. The latter is a potential adopter of the developed process, subject to suitable IP protection for the partners.

The need for advanced conductors has been established, and arises from the present situation in high-voltage transmission systems in Europe. Changed power flows in the network have arisen from liberalisation, closures of old power stations, and the feed-in of windmills, requiring new solutions to maintain security of supply. In the light of the existing competition from the USA a technical solution from within Europe is desirable. However, the result of the MACE program has not resulted in a wire with sufficient technical characteristics for the use in a conductor yet. In addition to overcoming the production difficulties, further developments will have to be made specifically to avoid corrosion. Further improvement in process control may bring the product to a higher quality level, and sourcing consistent high quality fibre may be an important part of that. Key consortium members remain willing, in principle, to engage in further activities, subject to establishing the necessary support.

Other opportunities in composite materials have been discussed with various contacts of the consortium. Aerospace is one sector that has been identified as of interest, and some discussions between interested parties and consortium members have taken place.

In summary, several avenues for further or diversified exploitation have been identified by the project partners. These include applications for the component technologies as well as for the EFRA wire itself. Of the technologies developed, potential exists for control systems, flux infiltration, die rounding, plasma deposition, tomography, conductor modelling and technico-economic assessments. Potential sectors and applications include photovoltaics, structural composites (e.g. in aerospace), process control, vehicle pollution abatement, and quality control, as well as the primary area of conductors.