INDUCTION HEATING OF CARBON FIBER STRUCTURES – PROPERTIES AND CHALLENGES

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Abstract: Carbon fiber reinforced plastic is constantly gaining market shares due to its unique properties. By heating this kind of materials using induction, many new applications occur. The high resistivity and anisotropic properties of carbon fiber composites means there are a number of challenges to overcome. This work emphasizes the key components related to induction heating of complex materials and present ways to characterize the important properties using non-contact methods. Successful experimental results are presented and the work also shows very good agreement between measurements and simulations.

Keywords: Induction heating, carbon fiber, CFRP, resistivity measurement

1 INTRODUCTION

Forming tools for e.g. thermoplastics, laminates and composites are traditionally built as solid blocks of metal, typically from aluminum or steel, in order to provide stiffness and wear resistance, but also to ensure an even temperature of the tool surface. Difficulties of uniform heating means that the heating generally is performed at the back side of the tool and a substantial amount of material is used to distribute the temperature evenly. A major drawback with these systems is the large thermal mass which leads to long settle times, another is high tooling costs. In processes based on constant tool temperature, the thermal mass only affects the start-up and shut-down time, while being devastating in terms of energy consumption and cycle time in processes demanding temperature cycling. Tool systems based on new materials and heating principles would be very beneficial in many industrial processes. Some composite materials have the potential to replace traditional metals for tool applications, one particularly interesting material is carbon fiber reinforced plastic, CFRP. Carbon fibers can combine high stiffness with good thermal conductivity and low thermal mass, together with flexible manufacturing of CFRP structures being crucial properties to allow building of thin-walled tools. Carbon fibers are semiconductors, with a resistivity of typically 100-1000 times that of copper, which means that resistive or inductive heating can be used, given the fibers form closed loops inside the plastic matrix (Fosbury, *et al.*, 2003).

A number of CFRP tool solutions based on resistive heating have emerged during the last decade or two (Staff, 2014), (Black, 2011). In (Staff, 2014) the power is supplied in embedded resistance wires, electrically insulated from the carbon fiber and distributed to provide a uniform temperature. In (Black, 2011) the heat in generated in a carbon foam, featuring a constant cross section and being located beneath the tool face, electrically insulated from the CFRP structure. Also composite tools based on liquids or gas medias for heating and cooling have been developed by a number of companies throughout the years. However, the most elegant solution would be to heat the CFRP tool structure directly, minimizing the heating time. While resistive heating requires constant cross section to obtain uniform heating, a number of induction heating principles to distribute the energy evenly have been developed in recent years (Fujita, *et al.*, 2010), (Wang, *et al.*, 2011).

Like metals, the properties of carbon fibers vary significantly depending on the raw material and processing, thus different qualities are beneficial for various purposes. This article will provide an overview of different carbon fiber types, the production and their properties both mechanically, thermally and electrically. The work will focus on the electrical resistivity, presenting and verifying a method of measuring the in-plane value with high accuracy.

The article explains how the measured resistivity affects the efficiency of induction heating at different frequencies using simulations. Also the thermal conductivity of the workpiece is an important property, linked to the resistivity as being discussed. Thermography results show isotropic heat propagation in high thermal conductivity CFRP structure based on local pulse heating using induction, not previously demonstrated. Historically and until present time, carbon fiber content in excess of 65% by volume is very rare, which means that the risk of insulation layers of plastic between the fibers at critical locations is severe. Today there exists methods to create CFRP structures with very high fiber content, exceeding 80% (Björnhov, *et al.*, 2011), which creates new opportunities.

2 CARBON FIBER COMPOSITE TOOLING

Tools made of CFRP have many advantages over traditional materials and with integrated fast heating and cooling capabilities it has the opportunity to change the range of materials used in many consumer and industrial products. With a cost effective way to produce components based on alternative materials, new products will see the market while others loose market shares. The CFRP solutions can outdo not only cheap material solutions like steel, aluminum and plastics as tool materials but also more expensive alloys like invar due to its lo coefficient of thermal expansion. However, a number of challenges must be solved to reach the whole way. One of these challenges is the thermal design and built-in stresses in complex shapes, solved by using proper fiber directions (Gomi and Kodama, 1991) or short-fiber bulk material (Hexcell, 2013). Processing of many materials also require temperatures in excess of 200 °C which demands high temperature resistance of the matrix material. Pushing the temperature limits of CFRP means an increased cost and complexity in the production but also a large commercial value.

Depending on the material to be processed, the surface of the tool must feature certain properties such as low friction, non-stick, high wear resistance, etc. However, CFRP structures are highly versatile and can be surface treated in the same way as metals, for example metallization by plating, various plastic and rubber treatments, as well as thermal spraying of ceramics. (Mitsubishi, 2014a) The low and negative coefficient of thermal expansion is an important reason why normally brittle materials can be used for coating.

The shape of the tools can vary from flat plates and rollers to complex 3D structures with surface textures. Some tools can be self-supporting while others requires reinforcements and support structures, independent of which, the CFRP structures feature competitive structural properties and means a significant saving of materials and machining since it can be built more or less net shape. By using optimized CFRP tooling, structures with very high thermal diffusivity can be obtained, reducing the thermal mass compared to alternative solutions.

3 CARBON FIBER COMPOSITES – PROPERTIES AND PROCESSING

Carbon fiber composites are constantly gaining market shares over more conventional materials such as plastics or metals. New fibers with better properties are continuously being developed and many new applications are found each year. Some of those changes have modest potential but once in a while major breakthroughs are made. Today there is, and have been for a long time, a consensus among researchers and industrial specialists that carbon fiber composites are of great importance for an environmentally friendly, sustainable future. The weight savings made possible by these materials correlates to large reductions in energy consumption when taking the entire life cycle of a product into account. The reduced mass of composite parts is, however, not the only benefit of using these materials. In their different compositions they can offer unique properties such as very high thermal conductivity and low electrical resistivity, enabling even more interesting innovations and applications.

The term carbon fiber is often used to describe a material as if its properties were unanimously defined. Truth is that it is a description that is just as vague as the term metal. There exists a great variety of fibers with extremely different properties. Despite the differences in properties, most carbon fibers are created by almost the same method and the only major variable is the raw material. The process of carbon fiber manufacturing consists of four major steps:

1. Spinning of raw materials to create precursor fibers
2. Stabilization in an oxidizing atmosphere
3. Carbonization in an inert atmosphere
4. High temperature carbonization / graphitization in an inert atmosphere

Those steps are common for both the manufacturing of standard modulus as well as ultra-high modulus fibers, differences lies mainly in the choice of precursor material and process temperatures in the final steps. The manufactured carbon fibers are generally surface treated, often using oxidization and then being exposed to a thin layer of sizing. The complete chain in the manufacturing is illustrated in Fig. 1.

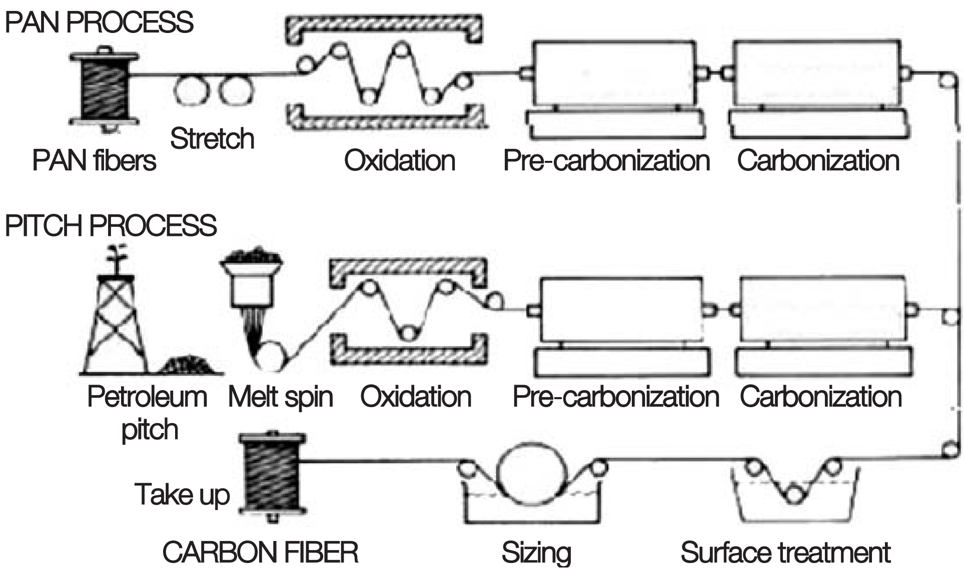


Fig. 1. Illustration of the manufacturing process of carbon fibers. (Khan, *et al.*, 2008)

Not only the fiber properties affect the final material properties but also the type and amount of binder, fiber directions etc. are crucial. Generally the higher fiber content the better electrical and thermal conductivity of the structure, but also the more difficult to produce. The manufacturing of the fiber structures can be done in a number of ways, such as weaving, filament winding or fiber placement. The matrix material can be a thermoplastic or a thermoset, where the latter is by far the dominant one, typically consisting of epoxy resin. A large variety of ways to combine the fiber with the matrix exists, from pre-preg systems to resin transfer molding etc. The manufacturing can significantly affect the electrical properties of the composite, however the manufacturing itself is not of particular interest in this work.

The type of carbon fiber is a dominant factor deciding the limits of the material. The most commonly used precursor is polyacrylonitrile, PAN, accounting for approximately 90% of the entire market (Jin, 2014), and used to produce fibers with a wide range of properties. Another common precursor is the mesophase pitch which is used to produce ultra-high modulus carbon fibers, but also fibers with very high thermal conductivity. Other precursors exist as well and are in use today, such as rayon, cellulose, lignin, phenolic resins and many others. Most of those are very hard and expensive to use or have insufficient performance and are not furthered discussed here. PAN based fibers feature high strength and is easy to use in a manufacturing process but suffer from lower values of thermal conductivity and young's modulus than the mesophase pitch fibers, which are more brittle. Fig. 2 summarizes the electrical resistivity and thermal conductivity for PAN and pitch[1] fibers, with some common metals as references.

4 INDUCTIVE HEATING OF CFRP STRUCTURES

Induction heating relies on two physical principles of heat generation, resistive losses and magnetic hysteresis effects. Unlike the hysteresis effect that only generates heat in materials with magnetic permeability much larger than one, the resistive losses acts on all electrically conductive materials and is also the dominant effect. The electrical resistivity of the workpiece material in combination with the geometry and frequency play important roles for the efficiency. The skin depth of the material, defining the distance into a material where the current density has been reduced by 63.2% compared to the surface current, at a given frequency, resistivity and magnetic permeability.

[1] Dialead is a registered trademark of mesophase pitch fibers.

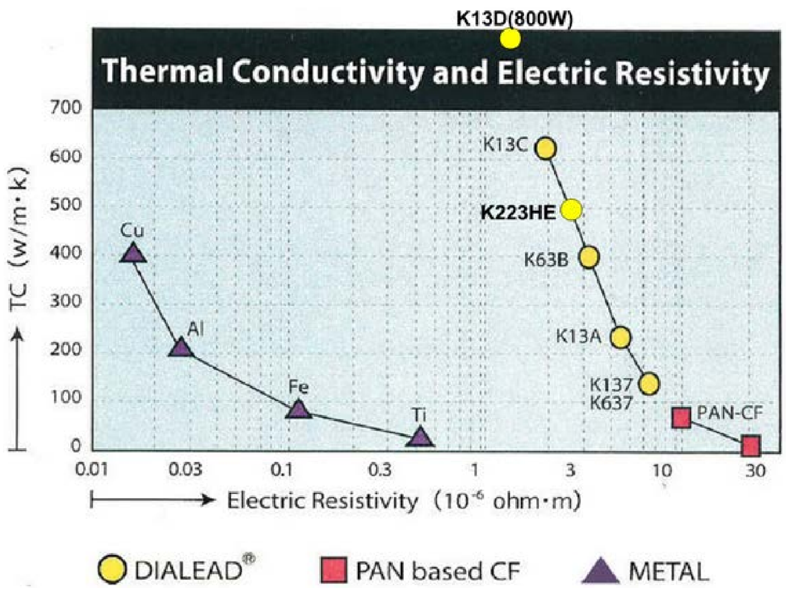


Fig. 2. Thermal and electrical conductivity of different carbon fiber materials at room temperature. (Mitsubishi, 2014b)

For workpieces being of a similar thickness or thinner than the skin depth, parts of the energy propagates through the workpiece. Fig. 3 illustrates the relation between the efficiency and the electrical conductivity and the efficiency when heating different materials respectively as functions of the frequency.

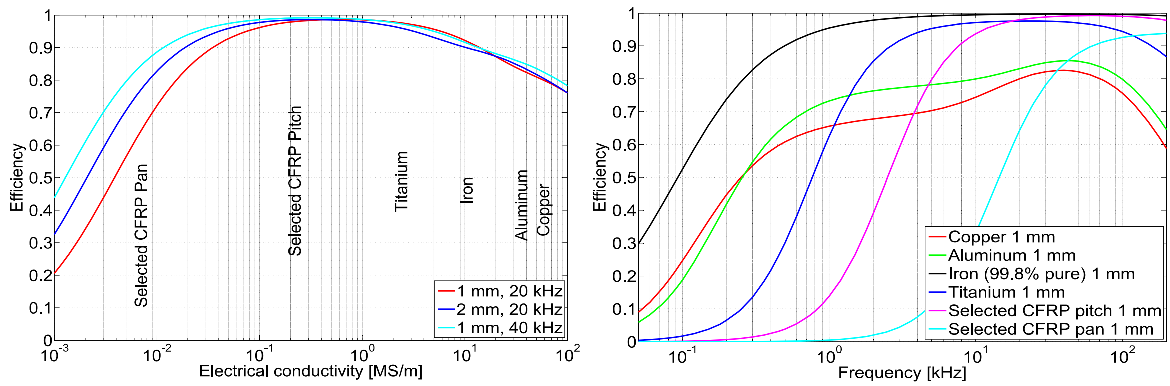
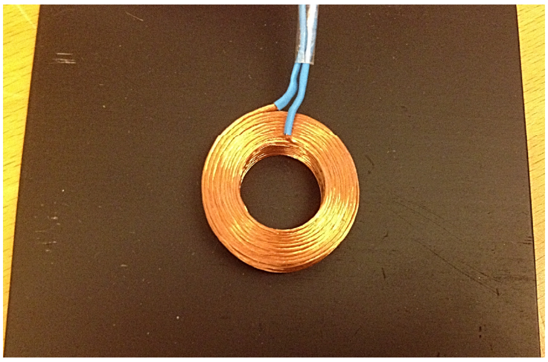


Fig. 3. Simulated efficiency values from the current in the coil to the heat in the workpiece. Left: Function of electrical conductivity, frequency and workpiece thickness. Right: Function of frequency for different materials. (Frogner, 2014)

While metals usually have an isotropic resistivity, CFRP generally don't, which creates a more complex task. Depending on the fiber directions, the resistivity can be many times, with the highest value perpendicular to the fibers. Also different fiber types affect the properties significantly, something that make it possible to design materials with desired properties, but can also be a challenge in many applications. The general conclusion is that the relatively high resistivity of CFRP materials demands higher excitation frequencies compared to metals, especially for heating of thin laminates. The coil must also be designed with respect to the fiber directions rather than something else.

5 CONTACTLESS MEASUREMENT OF RESISTIVITY

To measure the electrical resistivity is generally a simple task, but when it comes to a CFRP component, the contact condition plays an important role. Instead a solution is to measure it inductively using a coil, based on the same effects as being used for inductive heating. To avoid non-linear effects from soft magnetic materials, an air wound coil was manufactured from fine stranded, 30x 0.1 mm in diameter litz wire. Litz wires have all the strands individually insulated from each other and accurately twisted to have the same high frequency resistance in all of them. The measurement coil, featuring 108 turns was then placed adjacent to the test object according to Fig. 4. Using a LCR-meter, Hameg 8118 and sweep the frequency, the resistance and inductance curves can easily be obtained, shown in the same figure.



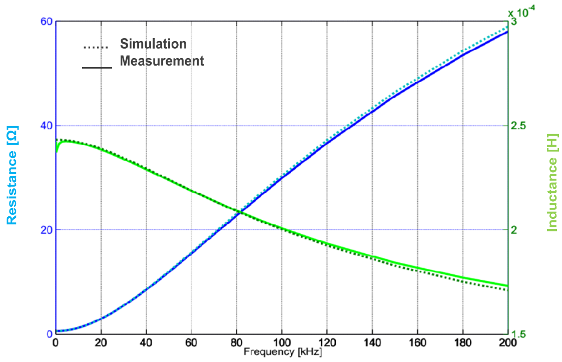


Fig. 4. Left: Picture of the setup with CFRP plate and measuring coil to determine the in-plane resistivity of the structure. Right: Measured and simulated results of resistance and inductance of the setup as a function of the frequency.

An axi-symmetric FEM-model of the setup was developed and simulated with current densities and magnetic flux densities according to Fig. 5. With an optimization routine, finding the least square fit of the resistance and inductance curves in a selectable frequency interval, the resistivity could be determined with good accuracy. Fig. 4 show very good agreement between simulation and measurement. Using this method, a number of CFRP plates, with different fibers and with different structures have been characterized.

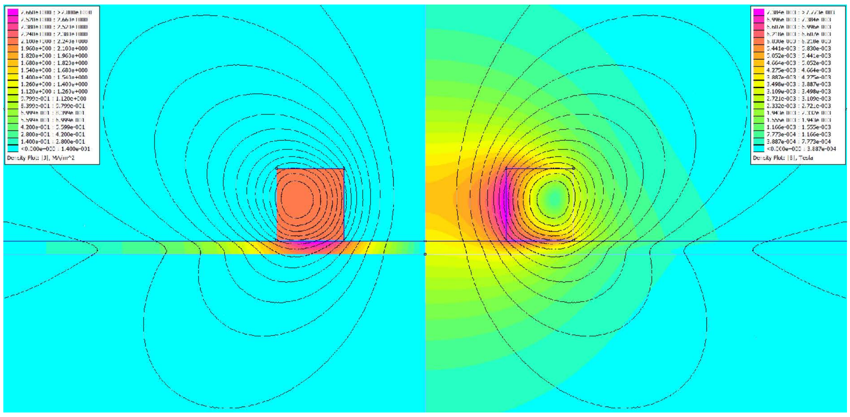


Fig. 5. Post-processed simulation model, left: current density, right: magnetic flux density.

The resistivity of high volume fiber (>70%), 0/90° multi-layer plates made of K13D2U-fiber was measured to an equivalent in-plane resistivity of 4.6 $\mu\Omega$m while similar plates made of K13C6U feature a value of 6.2 $\mu\Omega$m. Woven PAN-fiber plates was measured to 50-65 $\mu\Omega$m, but also higher values was occasionally obtained depending on the packing density, fiber directions etc.

6 EFFECT OF THERMAL CONDUCTIVTY

The mesophase pitch fibers feature very high thermal conductivity, a property that is particularly important in tooling applications since a high value aims to reduce the thermal gradients. A very important property of many materials and carbon fibers in particular is the relation between electrical resistivity ρ and the thermal conductivity κ that can be modelled for example by Lavin-Issi Correlation, an empirical formula specially developed for mesophase pitch fibers that works pretty well, equation 1. (Lavin, 1993) The units must be W/mK and $\mu\Omega$cm respectively. Also alternative empirical formulas exists (Gallego, *et al.*, 2000) and by looking in Fig. 2 it is clear that the two properties are linked together.

$$\kappa = \frac{400000}{\rho + 258} - 295 \tag{1}$$

Since the thermal conductivity as fairly difficult to measure with high accuracy, the relation to the electrical resistivity, which is significantly easier to define, can be useful. The thermal conductivity along the fibers, for example in a uni-directional plate can be approximated by the rule of mixture, while the propagation of heat between fibers is significantly more complex. The thermal conductivity can also affect the induction heating efficiency of CFRP structures since the resistivity is generally temperature dependent, however, for small temperature changes the effect is not significant.

In a real application, the thermal conductivity only provides a part of the searched information, what is the interesting property is the thermal diffusivity; the conductivity scaled with the thermal mass. By heating a spot or ring on a number of different materials; titanium, ferritic steel, aluminum and mesopitch-based CFRP made of K13D2U-fiber to a given temperature using a short induction heating pulse, the effect of the diffusivity is obvious. The test objects, 105x120x1.5 mm were heated from room temperature to about 100 °C peak in 0.1 s and the temperature was recorded using thermography, Fig. 6. The used coil was the same as being used to measure the resistivity, with an outer diameter of 30 mm, in this case being equipped with a soft magnetic composite core. From this experiment it is obvious that the CFRP plate distributes the heat significantly faster than the other materials and reaches a perfectly uniform temperature profile in less than 10 s.

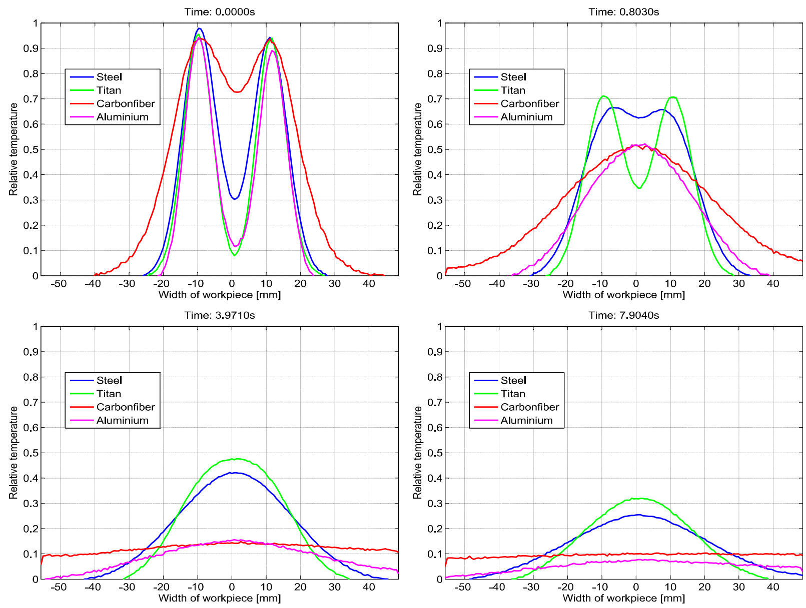


Fig. 6. The relative temperature profile, crossing the center of the heated ring, for different materials at different time, starting with time 0 s after the workpieces have been heated for 0.1 s.

7 RESULTS AND DISCUSSION

This work has shown that the in-plane resistivity of 0/90° CFRP structures can be accurately measured according to FEM simulations using a non-contact, inductive measurement method. In-plane resistivity down to 4.6 $\mu\Omega$m was measured on high volume fraction mesophase pitch CFRP-plates, being very suitable value for heating using induction according to simulations. The measured resistivities are about 3-4 times that of the pure fibers, meaning

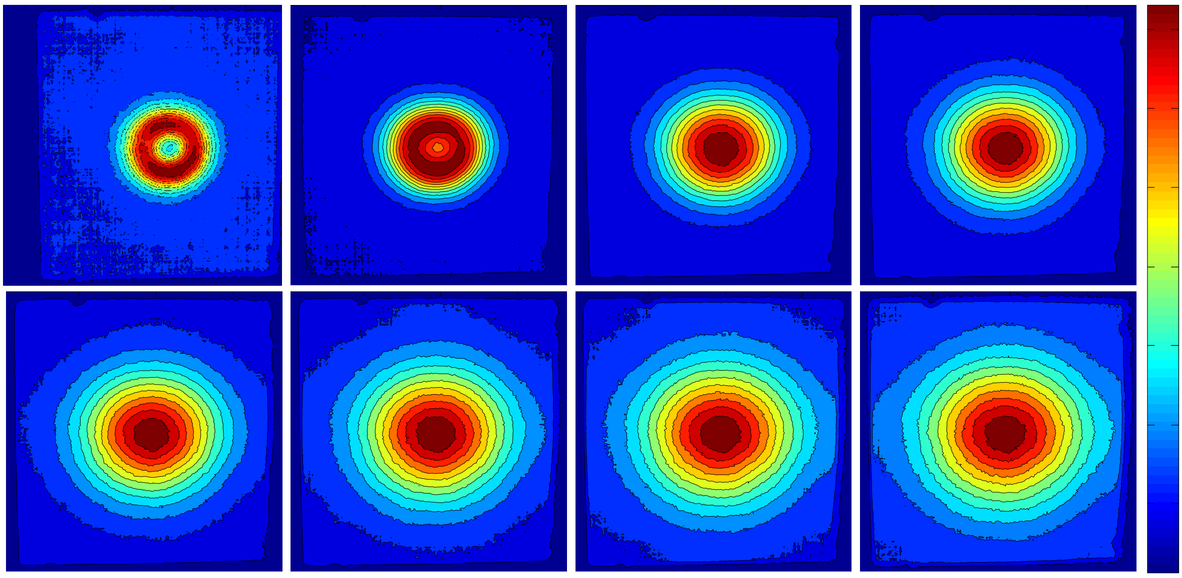


Fig. 7. Normalized isothermal heating pattern for different times during and after induction heating of a small ring in a CFRP plate.

good contact between the fibrils but leaving some margins for improvement of the fiber packing. Experiments have also shown that in-plane isotropy of the thermal conductivity can be obtained from 0/90°-structures according to Fig. 7, which means that there is a good thermal conductivity as well as electrical conductivity between different fiber layers. Considering the high conductivity properties of the fiber, 800 W/mK, a heating pattern propagating like a cross could be expected, but instead the isothermal lines in the figure expand radially like circles. From Fig. 6 it is clear that the CFRP plate outdo all tested materials, including aluminum, in terms of temperature equalization. The results emphasize the usefulness of CFRP, not only for tooling applications.

8 ACKNOWLEDGEMENTS

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