DEVELOPMENT OF A PROCESS TO BUILD POLYIMIDE INSULATED MAGNETS FOR OPERATION AT 350 C

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***Abstract* — An extensive R&D program has been conducted that has confirmed the feasibility of designing and fabricating copper alloy magnets that can successfully operate at temperatures as high as 350C. The process, originally developed for the possibility of manufacturing in-vessel resonant magnetic field perturbation (RMP) coils for JET, has been optimized for insulated magnet (and, potentially, other high temperature component) applications. One of the benefits of high temperature operation is that active cooling may no longer be required, greatly simplifying magnet/component design. These elevated temperatures are beyond the safe operating limits of conventional OFHC copper and the epoxies that bond and insulate the turns of typical magnets. This would necessitate the use an alternative copper alloy conductor such as C18150 (CuCrZr). Coil manufacture with polyimide is very similar to conventional epoxy bonded coils. Conductors would be dry wound then impregnated with polyimide of low enough viscosity to permit saturation, then cured; similar to the vacuum pressure impregnation process used for conventional epoxy bonded coils. Representative polyimide insulated coils were mechanically tested at both room temperature and 350C. Mechanical tests included turn-to-turn shear bond strength and overall polyimide adhesion strength, as well as the flexural strength of a 48-turn polyimide-bonded coil bundle. This paper will detail the results of the testing program on coil samples. These results demonstrate mechanical properties as good, or better than epoxy bonded magnets, even at 350C.**

Keywords-component; Magnets, Coils, Polyimide, Elevated temperature environment, Mechanical testing

I. BACKGROUND

The ability to have in-vessel magnets that can operate at 350 C originated with the designs and feasibility studies for resonant magnetic field perturbation (RMP) coils to control edge localized modes (ELM's) in JET. The details of the program requirements leading to a pre-conceptual design of two rows of ELM coils to be positioned inside the JET vacuum vessel has been documented in detail previously [1, 2, 3]. These ELM coils were designed to carry up to 60 kA-turns of current and would be of two different sizes.

The coils are mechanically grouped in eight sets, each set consisting of one large and three small coils, straddling adjacent octants inside the JET vacuum vessel. The large coil measures 1.5m × 0.3m in overall dimensions, while the small coil measures 0.8m × 0.3m. Each coil would be constructed of wound copper alloy conductor, which will be insulated, encapsulated, and encased in a vacuum-tight Inconel 625 enclosure. The encased coils would be mounted onto structural beams along the vacuum vessel wall.

After several iterations, the basic cross section for each large upper ELM coil is a 48-turn configuration with a 6 radial by 8 poloidal turn cross section (Figure 1). Each turn is capable of handling up to 1.25 kA, for a total of 60 kA-turns for the coil. Each turn measures 6.35mm x 6.35mm with slightly rounded corners to avoid sharp edges. There is a one millimeter space between turns to allow for Kapton film, glass, and the insulating bonding agent. There is a two millimeter space between the coil bundle and the Inconel 625 case to also allow for Kapton, glass overwrap and bonding agent. A large coil is estimated to weigh approximately 110 kg. The coil cross section typically measures 70mm × 55mm.

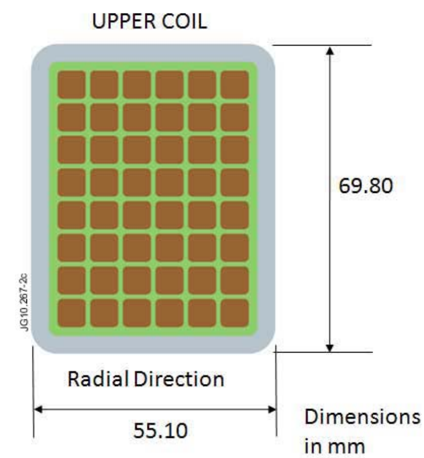

Fig. 1 Cross section of a large JET ELM coil

The ELM coils must withstand vacuum vessel bakeout at elevated temperatures (350 C) for extended periods, and must operate with the vessel at 200 C. Pulsed coil heat loads due to Joule heating of the conductors and radiation from the plasma must be handled. Cooling by both active and passive means was considered. Both were deemed feasible, but passive cooling was chosen because its risks were judged to be more manageable [1]. One overriding concern with active cooling was the complexity of installing leak-proof hydraulic fittings via remote handling.

Passive cooling means that the design must rely almost exclusively on radiation to the vacuum vessel walls for removal of pulsed heat loads between pulses. Coil overheating protection is provided by control of the ambient temperature

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and of the coil current and pulse length. The risk of damage can be mitigated through careful design and control, since adiabatic coil temperature rise can be reliably predicted. The consequences of overheating, should it occur, are likely to be confined to the coil system.

II. Materials Selection For Operation At 350 C

Due to the unique thermal conditions that require performance for repeated extended periods up to 350 C without active cooling, the selection of materials to build these coils is crucial. A detailed survey of a wide range of material options was undertaken and the material choices made as follows:

Coil conductor – Copper-Chrome-Zirconium (CuCrZr – C18150) – Conventional copper will lose its integrity and soften at 350 C. Therefore, another conductor material was sought. The decision to select CuCrZr was based on the extensive database of material properties available, especially via ITER. Test data verifies that exposing CuCrZr for extended periods at 350 C will not cause over-aging [4].

Coil case & supporting hardware – Inconel 625 – Chosen for its high temperature integrity, high strength, weldability, and experience with JET, Inconel 625 is an ideal choice for the JET ELM coil case and supporting hardware.

Coil insulation – Kapton and fiberglass cloth - each turn of conductor will be spray coated with a layer of Kapton film followed by wrapping in fiberglass cloth. There is a great deal of experience with both materials for winding coils. These materials provide an extra measure of protection against potential turn-to-turn electrical shorts. It should be noted that a spray-coated Kapton conductor, alone, cannot be relied upon as the primary electrical insulation barrier. That is the job of the glass/bonding agent matrix.

Coil encapsulation / bonding – Polyimide – There are several commercially available candidate polyimide bonding compounds that can be vacuum impregnated, in a manner similar to the conventional vacuum pressure impregnation (VPI) of epoxy, by a process known as resin transfer molding (RTM). Originally developed for aerospace engine components, polyimide has all of the desired specifications and application experience, including bonding components wrapped in glass cloth, that make it well suited for manufacturing coils. Candidate polyimides will not break down at temperatures lower than 370C while maintaining an adequate adhesive bond strength along with an adequate short-beam shear strength that do not deteriorate at temperatures up to 350 C. Due to the fusion community's inexperience with polyimides for magnet applications, an extensive R&D program was undertaken to verify the manufacturer's performance claims.

III. Polyimide Bonded Coil R&D Program

In 2009, polyimide was selected as the material best suited to accomplish the aforementioned goals to manufacture JET ELM coils. An initial test program extensively tested the polyimide to confirm that it would meet the established performance limits by verifying the manufacturer's listed properties [3]. Hands-on experience was gained by working with the polyimide as an electrically insulating bonding agent and crucial experience was gained regarding the limits of the coil fabrication process. Most notably, the viscosity for polyimide is higher than standard epoxies requiring a relatively high pressure for impregnation. In addition, the polyimide RTM process and subsequent curing, occurs at elevated temperatures in excess of 350C. Accordingly, the goals of the original R&D program included:

- Confirm the ability to impregnate and cure dry-wound representative ELM coil samples with polyimide
- Confirm saturation of samples via visual inspection
- Confirm minimum 2 kV voltage standoff of post-cured samples
- Measure outgassing of post-cured sample
- Mechanical testing of sample to determine key properties (including modulus, shear/bond strength and flexural strength)

The results of the initial test program indicated several slight design modifications (discussed below) that would improve both the manufacturing and test results of these prototype coils.

A. Manufacturing of the Coil Test Articles

In order to test representative coil samples, several 0.6 meter long coil bundles, with the cross section shown in Figure 1, were built for the R&D program (Figure 2). Note that the alternating ends of the turns have short Macor spacers that enable accurate turn-to-turn electrical testing of the samples both before and after the impregnation with polyimide. Once cured with polyimide, these short Macor ends of the bundles were removed prior to mechanical testing. Also note that commercially available copper bar with a spray coated layer of Kapton was used as a cost and time-saving measure. For the purpose of evaluating the properties of the polyimide, the use of copper in place of CuCrZr does not affect the results of this study and is much more readily available. The Kapton coating for the conductor serves two purposes – first, it electrically insulates the conductor; and second, the polyimide has the potential to react with copper at elevated temperatures (the Kapton coating will help prevent this). Initial bundles in this R&D program used copper bar with half-lapped layers of bonded tape. Unfortunately, the adhesive used to bond the Kapton tape to the copper bar fails at 350 C and became the 'weak link' in the initial shear and flexure testing. While spray coated Kapton does not lose its integrity at 350 C, it is not as good of an electrical insulator as half-lapped tape due to tiny spots sometimes missed when applying the film coating. Ultimately, the glass-polyimide matrix is relied upon as the primary electrical insulator with the Kapton coating acting as a secondary layer. Each Kapton-coated copper bar (and then, the entire bundle) was wrapped with half-lapped fiberglass cloth.

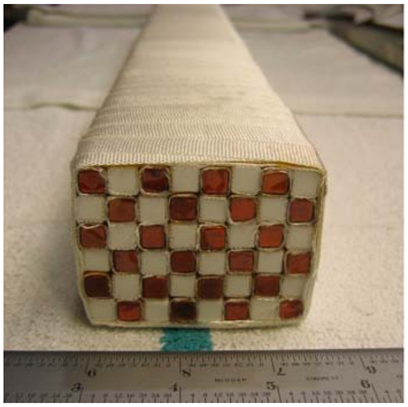

Fig. 2 Dry-wound coil R&D test sample, wrapped in fiberglass, with Macor spacers, prior to impregnation.

Once complete, each bundle was placed in a custom made steel mold which was coated with a mold-release agent, then bolted closed and sealed for the polyimide RTM process. Because of the complexities involved, the RTM was performed at a vendor experienced with both the polyimide and the RTM process. The details of the RTM process itself are proprietary.

Following the RTM and curing of a coil sample, it was removed from the mold once it had cooled down.

B. Electrical Testing

Each turn of a dry-wound coil bundle (Figure 2) was electrically tested to a 2 kV voltage standoff. For the post-cured sample, the ends of the bundle were cut/ground exposing the copper/Macor faces and then tested again to 2 kV. For all turns of all the samples, there were no indications of any electrical deterioration or degradation at all.

C. Visual Inspection of Cut Samples

Following the electrical tests, approximately 4 cm were cut off each end of each bundle thereby removing the Macor regions with margin. The interior of the RTM'd bundles could now be inspected at both the input and output ends of the RTM process to check for polyimide saturation and consistency. Figure 3 shows a close up of a typical bundle after the Macor section has been removed. With early bundles, the saturation of the bundle with cured polyimide appeared uniform. However, upon closer examination, small voids and shrinkage cracks could be seen in the resin-rich areas where the rounded corners of four copper turns met. There were no observable voids in the glass wound regions. This is a common occurrence even with epoxy and was virtually eliminated by placing additional glass rope/roving at these intersections. This was done for all later bundles and can be seen in the extreme close-up shown in Figure 4. The consensus is that following some preliminary testing, the quality of the RTM impregnation was uniformly excellent and consistent in all manufactured coil samples. The process can be repeated and the same quality of coil, without noticeable voids or dry spots, can be assured.

Fig. 3 Typical post-cured bundle section.

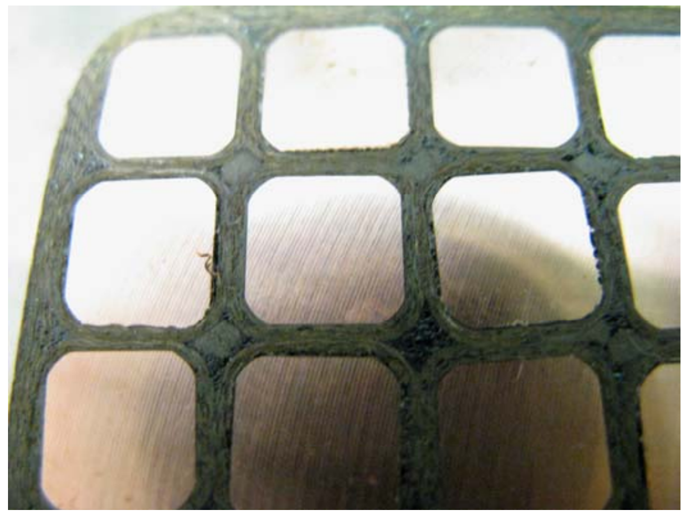

Fig. 4 Extreme close-up of cured bundle showing fiberglass rope/roving at turn intersections.

D. Outgassing Tests

Samples from early bundles were placed in a vacuum oven at 350 C for 24 hours for the purpose of measuring any outgassing from the cured coil samples. Outgassing is important to quantify because of the potential to contaminate a plasma from coils mounted inside a vacuum vessel. Results have been previously reported in [3]. In summary, during the RGA bakeout of these samples, various compounds were released that could be directly attributed to the polyimide. After 12-hours, these compounds had dropped from the 10^{-6} torr range to 10^{-9} torr range, indicating that a post-cure one-time bakeout of the coils should help considerably with any long term outgassing issues. It is worth noting that these samples were not pre-cleaned or prep'd in any way other than dry wiping. Proper clean room conditions utilized in actual coil manufacture should mitigate the potential for outgassing even further.

E. Mechanical Testing

1) Compression Testing

Thick samples from the early bundles were tested in compression and have been previously reported in [3]. There were no observable issues or concerns. All testing data indicated linear elastic performance independent of load rate and directionality with a consistently measured compression modulus of approximately 1.72 GPa (~250,000 psi).

2) Shear Testing

An essential characteristic of these coils that needs to be measured is the turn-to-turn shear strength at both room temperature and 350 C. Slices were cut from the bundles that measured 2 cm (0.75-inch) thick. A plunger that is slightly smaller than a copper turn was used to push against a single turn of copper while the eight surrounding turns remained supported underneath (Figure 5). Load was applied to the plunger until shear failure was observed. This approach allows for the calculation of the turn-to-turn bond strength of the polyimide. When early coil samples failed due to the lack of adhesion between Kapton tape and the copper [3], the decision was made to switch to a thin layer of spray-coated Kapton film on copper. For the purposes of shear testing, this worked extremely well.

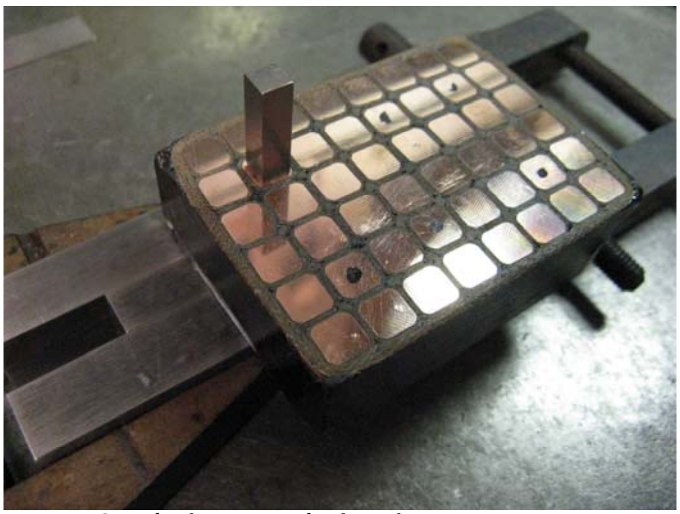

Fig. 5 Setup for shear testing of coil sample.

Room temperature shear failure was measured for numerous samples and found to be in a range between 13.0-20.4 MPa (1890-2970 psi). Two failure modes were observed. With each conductor turn individually wrapped in glass, one shear failure mechanism was at the glass interface between adjacent turns (Figure 6). Alternatively, the failure could also occur in the bond between the fiberglass and the Kapton coating of the turn (Figure 7). The shear stress was virtually identical for both failure modes.

The same shear testing was also performed at 350 C. The samples were placed in an air oven adjacent to the testing machine, then removed and quickly tested before the sample had a chance to cool. The results and failure modes were similar to the room temperature tests with a shear strength measured in a range between 11.0-21.5 MPa (1590-3120 psi). The only other difference between these two series of shear tests is that the elevated temperature samples had a tendency to discolor due to oxidation of the exposed copper, the reaction of the copper with the polyimide in air and the blackening of the plunger adhesive. All of these are considered to be purely cosmetic and would not occur in an actual coil, which operates in a vacuum with the copper not exposed directly to the environment. The polyimide vendor had made assurances that the adhesive bond of the polyimide would be a minimum of 7 MPa at any temperature between 20 C and 350 C. This was confirmed again by this latest series of shear tests.

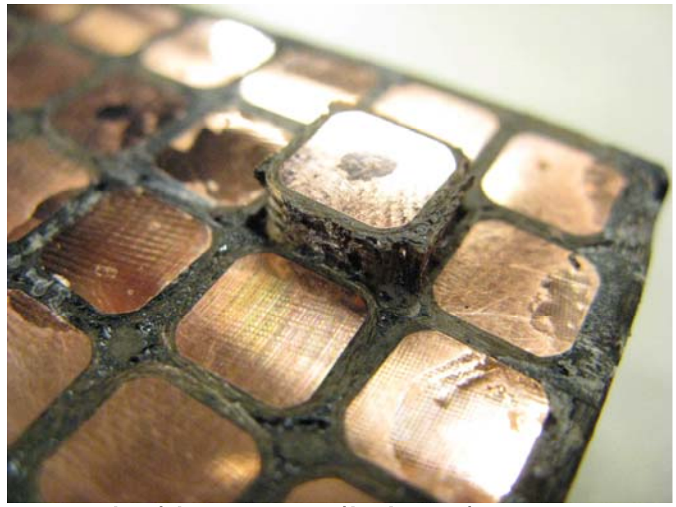

Fig. 6 Shear failure at turn-to-turn fiberglass interface.

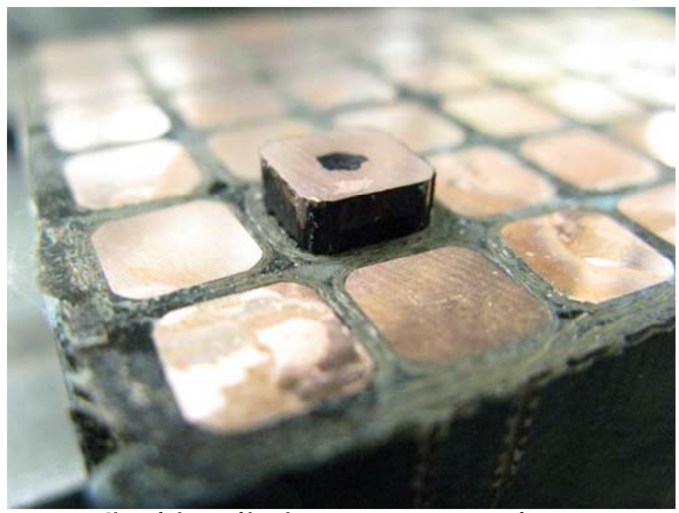

Fig. 7 Shear failure at fiberglass to Kapton coating interface.

3) Flexure Testing

A 0.33 m (13-inch) long length of one of the polyimide bonded samples with a 0.20 m (8-inch) free span was used to perform a three-point bend flexure test to failure at room temperature in accordance with ASTM standard D-2344 (Figure 8).

The failure mode in this test was expected to be tension cracking in the polyimide followed by the interlaminar shear failure in the polyimide bond between the fiberglass layers or the fiberglass-to-Kapton coating (similar to the shear test failure modes). However, in this test, the tension cracking on the underside of the beam was not followed by an observable shear failure. The integrity of the beam was ultimately compromised by the actual tearing of the fiberglass as the beam deflected. The beam showed a remarkable capacity for carrying load and the polyimide bond/shear strength was determined to not be a principal failure mode. The coil turns were not observed to slip relative to each other in any way, which would have been an indication of a shear-related failure.

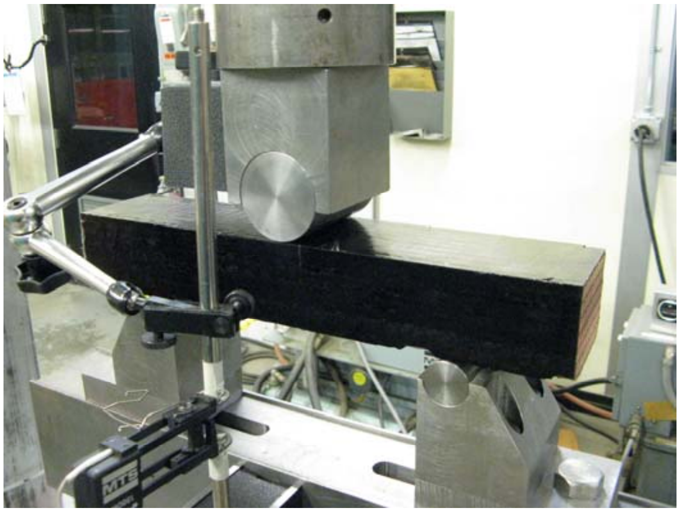

Fig. 8 Flexure test setup.

In this flexure test, the beam was able to reach a peak load of 72,700 N (16,350 lbs). Per the ASTM standard, the short beam strength is calculated to be 15.9 MPa (2,300 psi). This value far exceeds the calculated self-induced electromagnetic (EM) loads for a typical coil, including the JET ELM.

IV. Conclusions

Overall, this final phase of the R&D program demonstrated that the polyimide exceeded the limits advertised by the vendor and easily met all of the requirements of the JET ELM coil design. In summary, this R&D program demonstrated the following:

- The polyimide-bonded coil retains its integrity and mechanical properties under load at 350 C
- During curing, the polyimide has the potential to create small voids in resin-rich areas (similar to epoxies); this is resolved with the addition of more glass in those regions
- Outgassing is greatly reduced and nearly eliminated when samples are given a one-time bakeout in a vacuum for 12-to-24 hours at 350 C
- Electrical tests show that the voltage standoff is maintained to greater than 2 kV (post-cure)
- Spray-coated films of Kapton on the conductors are necessary to protect the copper from reacting with the polyimide during curing. Do not use half-lapped bonded Kapton tape because the adhesive is compromised at 350 C.
- Polyimide shear/bond strength is a minimum of 11.0 MPa and can be as high as 21.5 MPa, even at 350 C
- A polyimide bonded coil has a tremendous flexural capacity with a calculated short beam strength of 15.9 MPa
- The manufacturing/RTM process is consistent and repeatable

The ability to manufacture coils (and other components) with polyimide, via the RTM process has been confirmed with this R&D program. The ability to make coils that retain their structural integrity, even up to 350 C, without the need of active cooling, has been confirmed.

References

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