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Testing candidate interlayers for an enhanced water-cooled divertor target

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HIGHLIGHTS

- We introduce an optimised divertor target concept: the "Thermal Break".
- We suggest a candidate interlayer material for this concept: FeltMetal.
- We describe a bespoke rig for testing the thermal conductivity of this material.
- We present preliminary results for a number of samples.

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ABSTRACT

The design of a divertor target for DEMO remains one of the most challenging engineering tasks to be overcome on the path to fusion power. Under the European DEMO programme, a promising concept known as Thermal Break has been developed at CCFE. This concept is a variation of the ITER tungsten divertor in which the pure Copper interlayer between Copper Chrome Zirconium coolant pipe and Tungsten monoblock armour is replaced with a low thermal conductivity compliant interlayer, with the aim of reducing the thermal mismatch stress between the armour and structure. One candidate material for this interlayer is FeltMetal™ (Technetics Group, USA). This material consists of an amorphous matrix of fine copper wires which are sintered onto a thin copper foil, creating a sheet of approximately 1 mm thickness. FeltMetal has been successfully used for many years to provide compliant sliding electrical contacts for the MAST TF coils and on ALCATOR C-Mod and extensive material testing has therefore been undertaken to quantify thermal and mechanical properties. These tests, however, have not been performed under vacuum or DEMO-relevant conditions. A bespoke experimental test rig has therefore been designed and constructed with which to measure the interlayer thermal conductance as a function of temperature and pressure under vacuum conditions. The design of this apparatus and the results of experiments on FeltMetal as well as other candidate interlayers are presented here. In parallel, joint mockups using the candidate interlayers have been prepared and Thermal Break divertor target mockups have been manufactured, requiring the development of a dedicated joining process. These mockups will be subjected to high heat flux testing to further demonstrate the viability of the Thermal Break concept.

1. Introduction

1.1. Context

The design of a divertor target for DEMO remains one of the most challenging engineering tasks to be overcome on the path to fusion power. The decreased performance and overall lifetime due to increased neutron damage to the structural and armour materials, when compared to current machines and ITER, causes a significant challenge, particularly when coupled with the increased requirements for heat handling capability and material erosion lifetime.

1.2. Thermal Break divertor concept

Under the European programme, a promising concept known as "Thermal Break" has been developed at CCFE. This concept is a variation of the ITER Tungsten divertor in which the pure Copper

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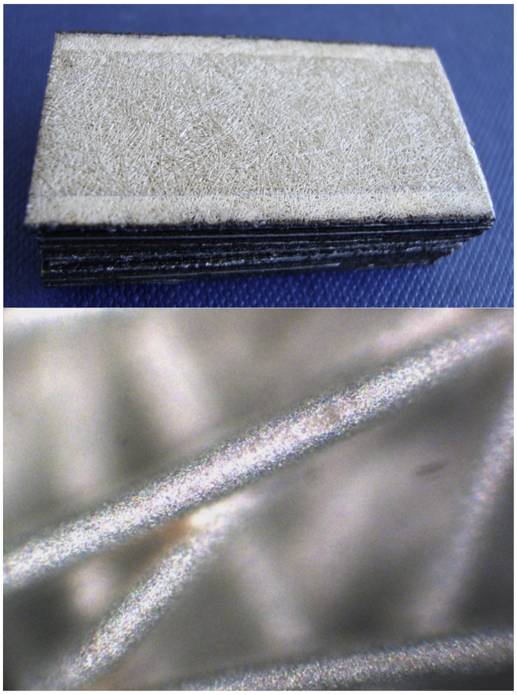

Fig. 1. Stack of 1 mm × 30 mm × 15 mm FeltMetal sheets and magnified (200×) photograph of silver plated FeltMetal.

interlayer between CuCrZr coolant pipe and Tungsten monoblock armour is replaced with a low thermal conductivity compliant interlayer, with the aim of reducing the thermal mismatch stress between the armour and structure.

An optimised version of this concept using irradiated property data and tailored interlayer properties, generated in 2013, was demonstrated to pass the ITER structural design criteria for in-vessel components and maintain a Tungsten surface temperature of <1300 °C when subjected to 10 MW/m^2 heat loads [1,2].

1.3. Candidate interlayer materials

One candidate material for this interlayer is FeltMetal^{TM} (Technetics Group, USA). This material consists of an amorphous matrix of 50 μm diameter copper wires which are sintered onto a thin copper foil, creating a sheet of approximately 1 mm thickness (Fig. 1).

FeltMetal has been successfully used for many years to provide compliant sliding electrical contacts for the MAST TF coils and on ALCATOR C-Mod and extensive material testing has therefore been undertaken to quantify thermal and mechanical properties [3]. These tests, however, had not previously been performed under vacuum or DEMO-relevant conditions.

Additional candidate interlayers for the Thermal Break concept have also been proposed. These include variations on FeltMetal such as using different thicknesses, materials and fibre parameters generated by advanced manufacturing techniques and alternative materials to more specifically tailor the properties of the interlayer. Analytical assessment of the relative impact of varying conductivity, thermal expansion, and Young's modulus is being undertaken within the Eurofusion WPDIV project and will guide the choice of interlayers to be explored in the next phase of this work.

1.4. Requirement for custom experimental apparatus

The conductivity of candidate interlayer materials must be well understood over a wide range of temperatures, vacuum conditions, and potentially under significant compression due to the thermal

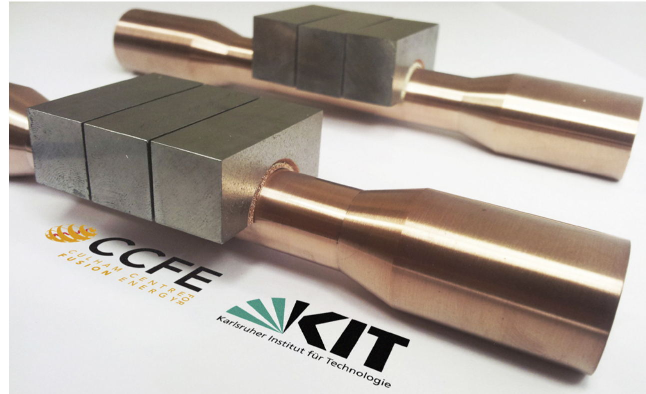

Fig. 2. High heat-flux mockups.

mismatch of armour and structural materials. While a number of methods exist for measuring thermal conductivity, including thermal flash and hot wire methods [4], these do not easily allow the samples to be subjected to the required pressures and do not lend themselves to testing conduction paths through more complex samples which include additional layers such as braze joints. The experimental apparatus detailed below provides a simple, flexible solution to these requirements.

1.5. Manufacturing trials

In parallel, joint mockups using the candidate interlayers have been prepared and Thermal Break divertor target mockups have been manufactured, requiring the development of a dedicated joining process. These mockups (two of which are shown in Fig. 2) will be subjected to high heat flux testing to further demonstrate the viability of the Thermal Break concept.

2. Design of vacuum thermal conductivity experiments

2.1. Mechanical design

An overview of the mechanical design of the experimental apparatus is shown in Fig. 3.

The experiment was centred around a 70 mm × 15.8 mm × 15.8 mm test piece mounted vertically between two copper holding pieces, as shown.

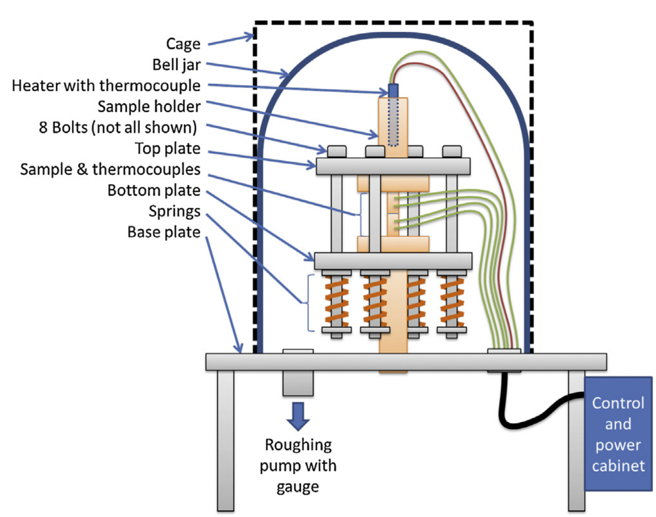

Fig. 3. Overview of thermal conductivity apparatus.

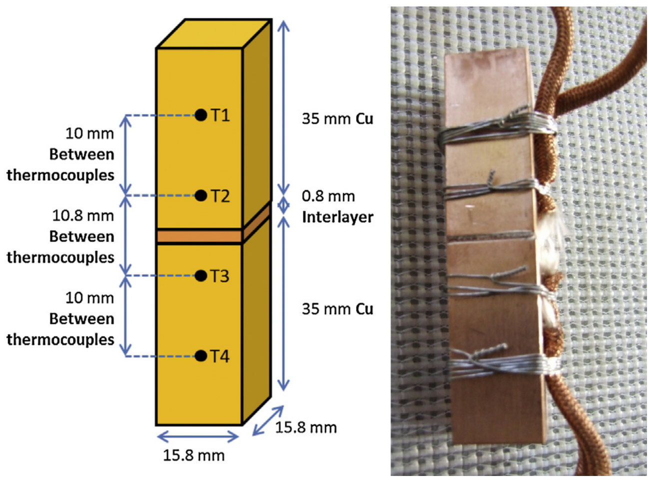

Fig. 4. Diagram and photo of FeltMetal sample with thermocouples.

In order to measure thermal conductivity of the samples under a well-defined load, the sample holders are connected via a cage of bolts and springs. By compressing these springs by a known amount, the load can be varied from a minimum corresponding to the weight of the assembly to a maximum of 40 MPa; corresponding to the maximum value calculated for the divertor concept.

The containing bell jar enables the pressure to be reduced to <10 MPa. This is considered more than adequate to reduce convection heat loss to a negligible value [5].

2.2. Experimental method

The thermal conductivity of the candidate material is determined using a simple 1D conductivity path through a square cross-section sample consisting of two identical Copper blocks between which the interlayer material is brazed using a Copper Silver Braze, as shown in Fig. 4.

One end of the sample is heated via a 400 W electrical element embedded in a mounting block. The aluminium base plate to which the assembly is mounted acts as a large convectively cooled heat-sink.

Eq. (1) shows how the power flux ($P_{1,2}$) between adjacent thermocouples $T1$ and $T2$ is calculated using the known thermal conductivity of Copper taken at the mean temperature (k_{Cu}), the cross-sectional area of the sample (A), the distance between the thermocouples ($x_{1,2}$), and the temperature difference ($T_1 - T_2$).

$$P_{1,2} = \frac{k_{\mathrm{Cu}}A}{x_{1,2}}(T_1 - T_2) \tag{1}$$

The four thermocouple measurements (T_1, T_2, T_3, T_4) allow calculation of the temperature either side of the candidate interlayer material (T_{i1} and T_{i2}). Eq. (2) shows the calculation for T_{i1}.

$$T_{i1} = T_1 - \frac{P_{1,2}x_{1,i1}}{k_{\mathrm{Cu}}A} \tag{2}$$

The conductivity of the interlayer material can then be calculated using the calculated temperatures (T_{i1} and T_{i2}), the power flux ($P_{1,2}$), and the thickness of the interlayer by the same method. Fig. 5 illustrates this process graphically; the gradients between T_1 and T_2 and between T_3 and T_4 are used to calculate T_{i1}, T_{i2} and the gradient between them.

The manufacturers' quoted combined error in absolute temperature readings from the K-type thermocouples and Pico datalogger used is ±2 °C. However, prior to testing in the rig above, the samples were placed in a temperature controlled oven and the readings compared over the temperature range of interest. The spread of temperatures for each sample was consistently <0.5 °C, giving much greater confidence in the precision of the final results than anticipated, and reducing the theoretical error in calculated conductivity of the FeltMetal to <10%.

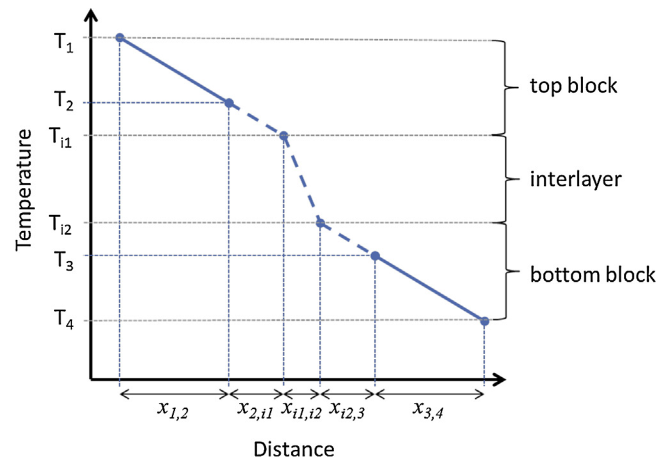

Fig. 5. Temperature distribution through sample.

The power through the entire sample should be uniform, since convection and radiation should be negligible and conduction should be 1D and constant. By comparing the temperature differences between the pairs of thermocouples in the top and bottom blocks, i.e. ensuring $(T_1 - T_2) = (T_3 - T_4)$, it can be confidently asserted that this is the case because of constant cross-sectional area and equal thermocouple spacing. Any difference can be used as a first indicator of the magnitude of total error in the thermal conductivity measurements. These errors may originate from transient effects due to heater control, from unexpected radiation effects, or from fluctuations in measured temperature at the datalogger. The percentage difference between $(T_1 - T_2)$ and $(T_3 - T_4)$ is calculated as shown in the following equation (Eq. (3)).

$$\%_{\mathrm{difference}} = \frac{(T_1 - T_2) - (T_3 - T_4)}{((T_1 - T_2) + (T_3 - T_4))/2} \times 100 \tag{3}$$

3. Experimental results

Two variants of FeltMetal were available to be tested: 0.8 mm and 1 mm thicknesses. Unfortunately, both variants included Silver plating on the Copper fibres. Un-plated tests are planned. In order to test the impact of joining methodology, samples were produced with and without additional Silver plating on the connecting faces of the Copper blocks. Results from five samples are shown below. Sample details are shown in Table 1.

Fig. 6 shows an example set of data for sample 1, including bounds set by the percentage difference in power as calculated above. The conductivity of FeltMetal is reported as a fraction of the bulk conductivity of Copper, since this is the parameter used during the design optimisation procedure for the Thermal Break Concept. For the optimised designs presented in [1], a value of between 0.08 and 0.1 was found to be ideal, dependant on other geometric constraints.

Table 1
Details of selection of FeltMetal samples.

Sample #	Details
1	0.8 mm FeltMetal, no plating
2	0.8 mm FeltMetal, no plating
3	0.8 mm FeltMetal, 15 μm Ag plating
4	1 mm FeltMetal, 15 μm Ag plating
5	1 mm FeltMetal, 15 μm Ag plating

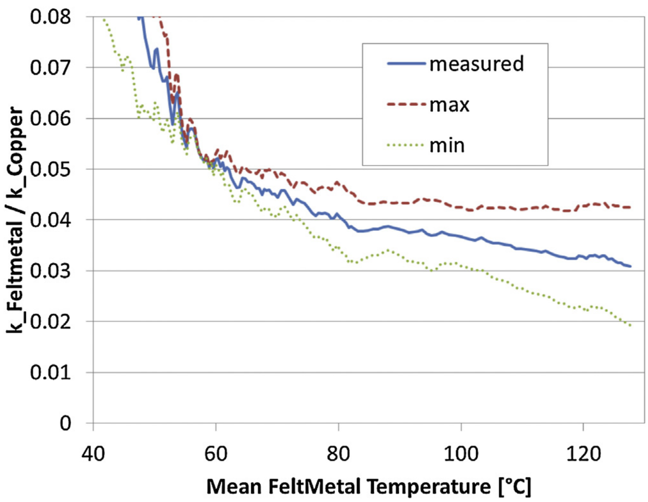

Fig. 6. Relative conductivity for sample 1, showing bounds of percentage difference.

The value of measured power above and below the sample fluctuated over the course of measurements, as shown in Fig. 7. For simplicity, therefore, Fig. 8 does not show the size of these potential errors. It would perhaps be prudent to apply a bulk error of ∼15% to the conductivity measurements, to be reduced in subsequent experiments by more careful control of the power applied.

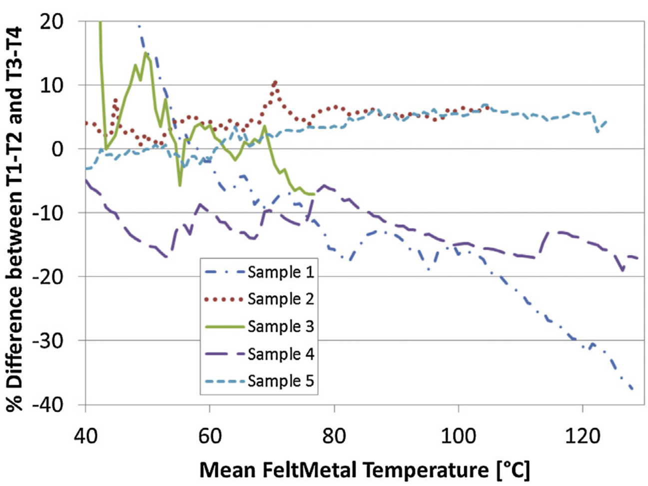

Fig. 7. Percentage difference between power measured above and below the interlayer.

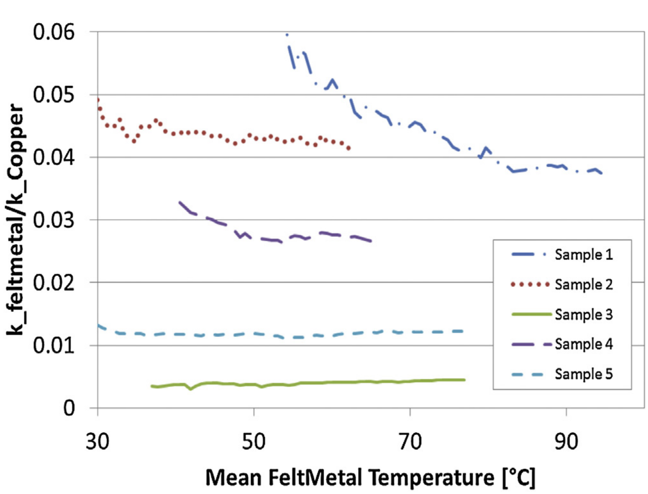

Fig. 8. Measured conductivity of FeltMetal samples, compared to bulk Copper.

The significantly smaller conductivity of sample 3 suggests that joining technique and additional plating may have a significant impact on the overall conductivity of the interlayer. The reduced conductivity of samples 4 and 5 and their relatively large variation indicates nonlinearity in conductivity with thickness, though may also indicate large sensitivity to compression.

4. Conclusions and next steps

4.1. Additional measurements using FeltMetal

The preliminary results presented here suggest that the conductivity of FeltMetal is close to that required by the optimised design in [2]. In addition, the Young's modulus reported in [3] also matches the ideal value of ∼1 GPa for the Thermal Break concept. Further tests on the samples reported above are required to increase confidence, however, including tests under compression. In addition, measurements will be performed measuring the conductivity of braze material and Silver plating independently from FeltMetal.

4.2. Improvements to apparatus

The relatively small sample size, modest temperature gradients, and inherent limitations of thermocouples, datalogger, and heater control mean that uncertainty in thermal conductivity calculations is larger than desired using the apparatus as described above. In addition, while ensuring that the power fluxes above and below the interlayer are equal provides some confidence in instantaneous measurements, real steady-state operation has not been achieved; the temperature measured at the base of the apparatus has not completely stabilised. Significant improvements can, however, be made with small modifications such as increasing the distance between thermocouples to increase measured temperature differences, improving heater control and power measurement to reduce fluctuations and raise maximum achievable temperature, and adding active cooling to the underside of the aluminium base plate to enable reaching steady state.

4.3. Additional interlayer materials to be tested

While lacking the precision of other methods of measuring thermal conductivity, the flexibility and simplicity of the method reported above means that this apparatus provides an attractive method for initial investigations of other interlayer materials and joining techniques. Further experiments are planned using both more conventional materials selected for their intermediate material properties between Copper alloys and Tungsten, and more complex structures manufactured using advanced techniques such as additive manufacturing processes.

4.4. High heat flux testing of mockups

In order to assess additional attributes of candidate interlayers such as manufacturing processes and high heat-flux performance, prototype mockups using candidate structural and armour materials have been manufactured and will be subjected to high heat flux tests as part of this ongoing work.

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