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Development of test facilities for thermo-mechanical fatigue testing

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ABSTRACT

Thermo-mechanical fatigue data is critical for the generation of appropriate lifing methodologies for a range of in-service applications where non-isothermal conditions are prevalent. Recently the development of more standardised testing approaches through appropriate code of practice documents and international standards has proved crucial. In the current paper, several methods of undertaking TMF testing are explored, with the benefits and pitfalls of each test type investigated. It is shown that bespoke test setups are often required, dependent on material, TMF cycle and specimen type. Further developments are suggested, along with a suggested methodology for TMF crack growth tests.

1. Introduction

In order to produce appropriate data for component lifing it is critical that mechanical testing is conducted under conditions which are truly representative of in-service environments. Only a limited number of applications produce operating conditions where uniaxial, isothermal testing can provide a database of characteristic material behaviour which can form the basis of constitutive models.

Multiaxial fatigue can be undertaken through a range of test techniques that produce biaxial or even triaxial stress states, including notched specimen tests, cruciform experiments and tension-torsion tests along with many others. However, non-isothermal environments have typically been difficult to accurately replicate, mainly due to the difficulties associated with controlling temperature accurately, even over the relatively small volume of material required for coupon testing. In particular, the field of thermo-mechanical fatigue (TMF) has long been hindered by the lack of consistency of generated test data, especially considering that codes of practice have only recently been developed for strain controlled TMF (2006) [1] and stress controlled TMF (2015) [2].

Two major factors influence the integrity of TMF test data, namely the ability to produce a homogeneous temperature distribution over the tested volume of material under a dynamic cycle, along with the ability to accurately measure the temperature in a manner which will not unduly influence the fatigue life of the test. Under strain control conditions, the representative volume of material is located between the extremes of the strain monitoring device which allows for a reduced volume of material within the specimen gauge length to be considered. However, in a stress-controlled test on a plain specimen geometry, it is critical that the entire gauge length is subjected to these considerations, which may be extremely challenging, dependent on specimen design. ISO12111 [3], the international standard for Strain Controlled TMF testing encourages the use of thermocouples (TCs) for temperature measurement, through either spot-welded, ribbon type or coaxial contact TCs. Ribbon type TCs are capable of measuring the direct temperature in the centre of the specimen's gauge length without risk of damaging the surface of the alloy. However, since they are wrapped around the specimen rather than welded to the outer surface, care must be taken to ensure that there is sufficient thermal contact between the test-piece and the thermocouple without any potential degradation during the period of the experiment through oxidation or roughening of the surface [4]. This method has not been widely used, seemingly due to a lack of consistency [5]. Instead, welded thermocouples have become the dominant method by which control has been established. Clearly, since the welding process causes a defect on the surface of the specimen, this process should not be applied within the critical volume of tested material, such as within the specimen gauge length, if the desire is to obtain an appropriate fatigue life under TMF loading [6]. The preferred technique has been to weld a thermocouple to the specimen shoulder and obtain a relationship between this control thermocouple and the temperature within the critical volume of material. However, more recently, a number of drawbacks in this method have been highlighted, with the consistency of the relationship questioned [7].

The ISO12111 standard [3] does however allow for non-contact measurements to be made through techniques such as pyrometry. Previous work has highlighted the difficulty with this process in materials where oxidation at high temperature influences the surface

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condition of the material, hence changing the emissivity value. In these cases, pre-oxidation treatments are often used to provide a stable surface condition, although the detrimental effects of this treatment also require consideration [8].

It quickly becomes clear that methods for testing materials under TMF loading conditions are extremely challenging, and require a great deal of consideration, with no standard test setup necessarily appropriate for all requirements. The authors have established through a number of previous research programmes the necessity to develop a series of bespoke setups and flexibility in approaches to provide the most appropriate test facilities, dependent on temperature cycle, material under investigation, surface finish etc. The current paper therefore seeks to highlight the pitfalls of certain approaches and suggest appropriate techniques for TMF testing of a selection of materials under different thermal cycles to act as a guideline for future development. The approaches are then validated through the development and demonstration of four bespoke setups, for which consistent and relatable data has been produced, allowing for greater confidence in each technique.

2. Development of experimental approaches

2.1. Induction coil heating with forced air cooling and pyrometry based temperature control

2.1.1. Heating method

The publication of ASTM E2368-10 [9] and, more recently, ISO12111 [3] strain-controlled TMF standards, highlights the significance of dynamic temperature effects on material fatigue behaviour. A homogeneous temperature distribution is crucial for the replication of TMF in a test laboratory. All of the standards published state the importance of achieving a maximum temperature gradient across the specimen (± 5 °C or ± 1%ΔT circumferentially at the gauge location and ± 10 °C or ± 2%ΔT axially) [1,2].

The desired thermal response during standard tests under isothermal fatigue (IF) can be achieved using a conventional resistance furnace, controlled and monitored by thermocouples (TCs). However, for the use of rapid dynamic thermal cycles, this technique is unsuitable, since the heating and cooling rates generated by the furnace are too slow to provide the dynamic temperature rates required. An ICS has previously been employed in several institutions [10]. With their ease of adaptation and the ability to be applied to existing test frames, ICSs are an attractive choice for heating within TMF testing. Offering a relatively inexpensive and reliable heating solution, their flexibility also enables the use of established fixtures and specimen geometries, leading to direct comparisons with previous IF test results [10]. ICSs function by passing an alternating current (AC) through a water-cooled copper induction coil to create an electromagnetic field. When a specimen is placed within this electromagnetic field, current flows against the resistivity of the alloy, producing eddy currents and thus resulting in the heating of the specimen. However, a downside to the technique is the homogeneity of the applied temperature, which is often far less uniform than in a conventional resistance furnace. In light of the requirements for reduced cycle time however, for this study, an induction coil system (ICS) is adopted for the heating cycle and air amplifiers are utilised for cooling to achieve temperature rates in excess of 15^0C/second.

2.1.2. Specimen design

Internal thermal gradients are dramatically reduced with the use of a tubular, hollow geometry. The thin wall of this specimen design also enables rapid heating and cooling rates and thus, short cycle times [1]. Therefore, for the purpose of this study, tubular hollow specimens of a nominal external diameter of 10 mm, internal diameter of 8 mm, and a parallel gauge length of 35 mm were used with a 12 mm uniaxial extensometer employed on this machine design, allowing a consistent temperature profile across the gauge length. It should be noted that this deviates from the code of practice, which states that “the parallel length of the specimen shall be 20% longer than the extensometer gauge length but shall not exceed the gauge length plus the width of the gauge to reduce the risk of failure outside the extensometer gauge length” [1]. However, previous work has displayed little evidence of failures outside the gauge length using this setup [11].

2.1.3. Test machine fixtures

The validated code of practice for strain-controlled TMF testing states that water-cooled grips should be utilised within a TMF test setup to not only allow quick cyclic stabilisation of the longitudinal temperature distribution within the gauge length, but to also provide stable thermal conditions during the test [1]. Whilst establishing a viable test setup, Evans et al [12] discovered that the use of large water-cooled grips acted as heat sinks, drawing heat away from the test piece and creating undesirable thermal gradients. Andersson et al [13] reported similar findings, also detecting an occurrence of barrelling due to the positioning of the water-cooled grips to the heated specimen gauge, thus recommending that the distance of the heated gauge length to the water-cooled grips should be as large as practically possible to diminish such effects. Following such research, the grip arrangement utilised in this investigation consisted of two metallic, uncooled threaded conical inserts, allowing a suitable means of connecting the grips to the hollow specimen, whilst also reducing the presence of undesired thermal gradients and any potential effects of barrelling.

2.1.4. Temperature measurement and control

Temperature measurement and control is considered a most critical issue in TMF testing and was in fact addressed by the European developmental code of practice to be a major source of data scatter during a round robin exercise [14]. Usually temperatures are measured and controlled using thermocouples, infra-red pyrometry or more recently thermal imaging cameras.

Through the detection of thermal radiation emitted from the specimen's surface, pyrometry is a non-contact method for determining the specimen temperature during TMF testing and has been utilised in this study. However, concerns have previously been raised regarding the use of pyrometers during high temperature applications as the technique is susceptible to the oxidation of the specimen surface over time [1,7]. Formation and growth of the oxide layer throughout a TMF test can lead to changes in the specimen’s coefficient of emission and therefore affect the temperature stated by the pyrometer. Therefore, to provide an accurate temperature measurement and/or control throughout a test, a pre-oxidised surface can be introduced prior to testing to ensure a stable emissivity value for the material [5]. Emissivity relates to the ability of a material to radiate infrared energy compared to a perfect blackbody for a given temperature. As such, emissivity is crucial for thermal measurements, since without knowing the emissivity of the object, it is not possible to determine the true value of its temperature [15]. Primarily the emissivity of an object depends on the type of material and its surface properties i.e. roughness [16].

When applying an oxidising heat treatment to the material surface, the emissivity of the test material can be characterised as a function of time and temperature prior to a full thermal profiling procedure. To determine the emissivity, the emissivity input values of the apparatus are adjusted until the temperature reading is equivalent to that shown by a welded TC located close to the point of the pyrometer beam on the surface. From a series of tests conducted on CMSX-4, the emissivity test temperature chosen was equivalent to the T_{MAX} of the thermal cycles, which in this case is 1050 °C. The emissivity value of 0.55 observed after 10 h exposure at 1050 °C was in agreement with values found within published literature [17], where standard emissivity values were as follows: Polished – ε = 0.12–0.32, Oxidised – ε = 0.37–0.85, Nickel Oxide – ε = 0.59–0.86 [18]. However, during dynamic thermal cycling the emissivity would be required to be adjusted in respect to a

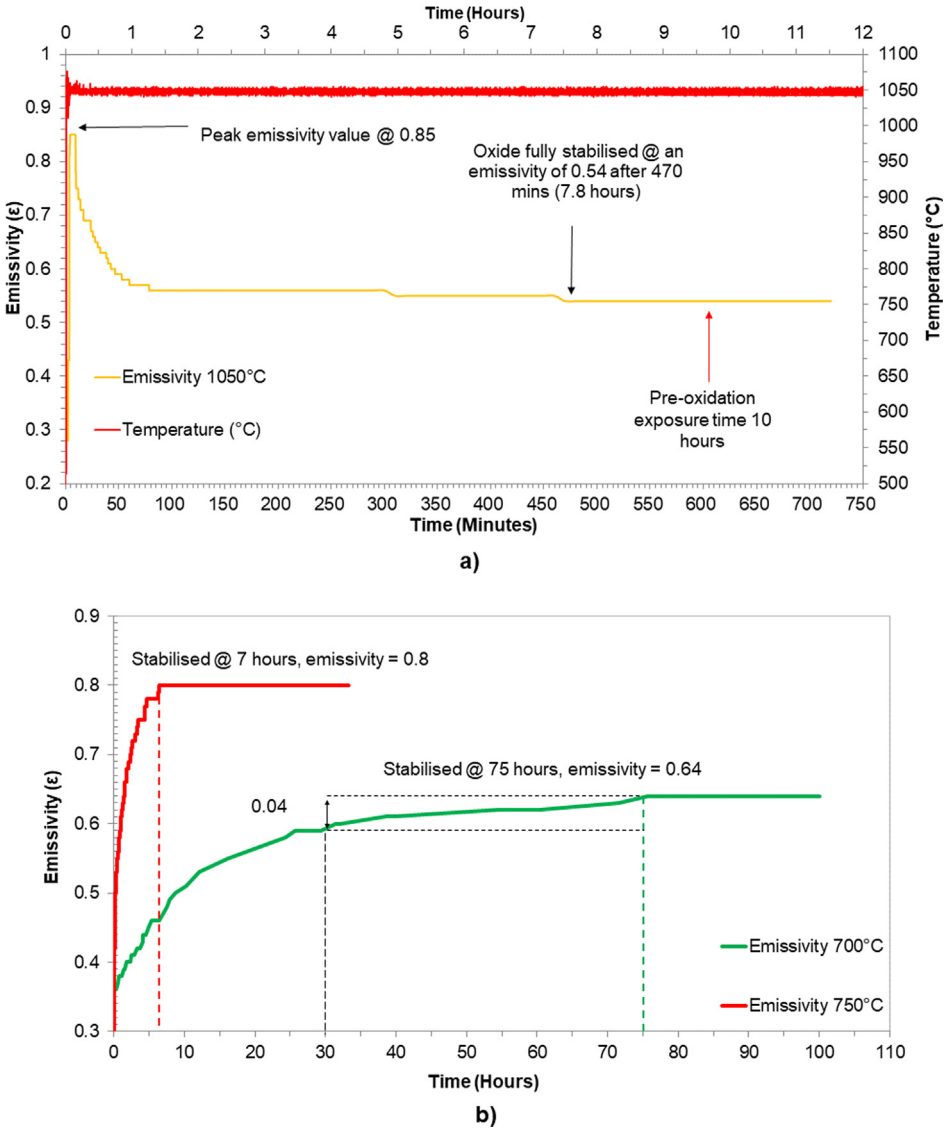

Fig. 1. Emissivity profile of (a) CMSX-4, showing the oxide stabilised at an emissivity of 0.54 after 7.8 h at 1050 °C and (b) RR1000, showing the oxide stabilised at an emissivity of 0.8 after 7 h at 750 °C and at an emissivity of 0.64 after 75 h at 700 °C.

monitoring pyrometer to account for the change in emissivity of the material during the test, the forced air cooling and the dynamic nature of thermal cycling.

At temperatures above 850 °C, CMSX-4 is found to oxidise rapidly [19]. As a result, the initial emissivity input values of the equipment are increased frequently to maintain accuracy with the TC, until T_{MAX} is achieved. Using such an approach, it is possible to determine the time taken for the oxide layer to grow to a point where the emissivity becomes stable. Whilst it is acknowledged that small variations will occur as the emissivity changes, these will be relatively small, and not alter the oxidation rates of the material. The change in emissivity with time for CMSX-4 is displayed in Fig. 1a, with a similar graph shown for the polycrystalline nickel alloy, fine grained (FG) RR1000, shown in Fig. 1b where a simple parabolic curve is demonstrated.

In determining an appropriate pre-oxidation procedure for the specimen, it is critical to achieve a balance between a treatment which provides a stable emissivity value but does not adversely affect the fatigue life of the material. Previous research by Bache [8] has shown that extended pre exposure of the test piece (100 h at 650 °C in this particular study) increased the incidence of initiated fatigue cracks and reduced the fatigue life at 300 °C by approximately a factor of 2. Given that the testing illustrated in Fig. 1b was also conducted on FG RR1000, and oxidation rates would be expected to significantly increase at 700 °C and 750 °C, pre-oxidation treatments were kept to the minimum period for which the asymptote of the emissivity vs time plot could be achieved, since this effect may particularly influence out of phase tests [6]. Clearly this illustrates however, the importance of developing an understanding of the emissivity variation with time ahead of TMF testing.

2.2. Quartz lamp furnace with novel cooling channels and non-contact thermocouple

2.2.1. Heating method

As previously mentioned, ICSs are a popular choice for TMF testing due to ease of use and relatively low cost. The formability of the coil to accommodate a multitude of extensometers, crack growth monitoring equipment, thermography cameras and cooling systems, is also a very attractive attribute.

When considering the use of an ICS, there are many factors that need to be considered. Firstly, it needs to be determined to what extent the material to be tested affects the choice of heating rates or power outputs required. It is therefore important to consider the material's electric resistivity and while ICS work with both conductive and semi-

conductive materials, including metals and silicon carbides, the difference in electric resistivity of the materials may result in a difference in heating rates. For example, a material such as steel would heat more easily due to its high resistivity, compared to aluminium which has a much lower resistivity and therefore would require a higher power output [20]. Therefore, when investigating the TMF behaviour of titanium metal matrix composites (Ti-MMCs), the uncertainty of achieving uniform heating in accordance to the code of practice [1] resulted in the decision to adopt an alternative heating method; a radiant lamp furnace.

A radiant lamp furnace was chosen as it can provide rapid heating rates whilst retaining line of sight to the specimen. Heating is provided by a 12 kW infra-red radiant lamp furnace (model number RHS2117) which has been modified and supplied by Severn Thermal Solutions. The radiant lamp furnace uses twelve high power vertically mounted quartz lamps to heat the specimen to the required test temperature. The furnace comprises of two longitudinally divided half cylinders hinged at the centre, with each half containing six lamps. Behind each lamp is a parabolic reflector, which focuses the radiant light towards the centre of the furnace. In addition, there are two quartz glass liners positioned to protect the lamps and at the same time providing a smooth channel for airflow around the furnace.

2.2.2. Temperature measurement and control

As previously mentioned, in most cases TCs are used for dynamic measurement and control of temperature during TMF testing and are outlined, in the code of practice, as an appropriate method [1]. Typically spot-welded to the specimen for temperature control, it is forbidden, by the code of practice, for TCs to be spot-welded within the gauge length as this can lead to a site of high stress concentration and potential crack nucleation [1,5]. Therefore, for the purpose of this study, the use of a TC spot-welded to the shoulder of the specimen, for temperature control, was explored.

The relationship between the temperature recorded at the specimen shoulder and the temperature recorded from within the gauge length needs to be a predictable one, in order to prevent long-term temperature drift within the furnace. This has been deemed possible to achieve with sufficient precision with heating and cooling rates of up to 10 K/s [5]. However, the accuracy and practicality of this technique under rapid dynamic thermal cycles has been questioned by Jones et al [7]; particularly when investigating specimens with a long parallel gauge length, where large distances exist between the TC location and the material section under investigation.

In order to validate this method, the temperatures measured at the shoulders were compared to that controlled by a TC located at the centre of the gauge length. The temperature variation is displayed in Fig. 2, in which it can also be seen that with time, the bottom shoulder TC also began to drift. The variation of temperatures between the TCs can be explained by two factors. Firstly, changes in temperature can be attributed to the larger surface area at the shoulders of the specimen compared to the centre gauge length location. Secondly, the shoulder location of the TCs is out of the hot spot of the furnace. The relationship between these TCs was deemed unreliable and thus it was decided that shoulder control in this case, was an unsuitable method. Fig. 2 shows that for the loops created, a polynomial function could not be adequately fitted. Therefore, the rapid cooling means that any polynomial fit would have to be an approximation and therefore would be unacceptable. Thus, it was important to determine a suitable alternative.

For the purpose of this study, the use of a non-contact thermocouple (NCTC) proved to be the most suitable option. The NCTC was chosen for control purposes due to the predictable relationship with the spot-welded control TC and the repeatability from test to test. Furnace mounting the NCTC ensures that the NCTC is positioned in a repeatable location between tests and also means that the furnace can be locked in place eliminating any variation in the thermal profile between tests. The predictable repeatable nature of the NCTC leads to a reliable thermal profile, as displayed in Fig. 2.

2.2.3. Cooling apparatus

With the use of a radiant lamp furnace as a heating method, it is important to ensure the cooling method adopted is sufficient, reliable and able to achieve the required cycle duration of 100 s, which was required for industrial relevance in implementing a 80–300 °C cycle representative of in service behaviour. Initially fitted above the furnace, around the upper loading column, an Exair air amplifier was utilised, providing rapid cooling rates from a top-down position. However, it was soon realised that this method of cooling was inducing large temperature gradients along the specimen gauge length. Therefore, achieving stringent temperature limits within the gauge length, as outlined in the governing standards, proved difficult. In order to overcome this issue an alternative cooling method was designed, in which the rate, uniformity and repeatability of cooling is improved. The set-up consists of four quartz cooling channels connected by a central ring. The channels run parallel to the specimen, each having five air outlets directed at the specimen as shown in Fig. 3. Replacing the original top-down cooling system, these channels provide a more uniform distribution of cold air across the specimen and thus leads to a more consistent thermal gradient across the specified gauge length as shown in Fig. 4.

2.3. Novel quartz lamp furnace with thermography control

2.3.1. Temperature measurement and control

Typically, prior to a test programme, an extensive dynamic thermal profiling procedure consisting of multiple stages is carried out to ensure that the volume of analysed material remains within the Code of Practice guidelines for temperature at all times within the cycle [1,2]. This process is usually convoluted and difficult, with significant concerns raised regarding the validity of measurements when thermocouples are removed, due to the effect of thermocouple ‘shadowing’. Any object that is close or attached to the surface of the test specimen will affect the way in which it is heated and cooled, and thus TCs with their insulation sleeving shield the specimen from cooling air and entrap emanated heat [7]. Jones et al [7] confirmed that 'shadowing' of TCs can have a significant impeding effect on a test specimen's thermal cycle, with the insulated TCs hindering the cooling by up to 20 °C, as presented in Fig. 5 [6,7].

Such issues, coupled with the limitations previously described for pyrometry, present a variety of issues when used for temperature control and monitoring. Furthermore, both of these methods are limited by the fact that they produce only point measurements of temperature.

The opportunity to test Silicon Carbide based Ceramic Matrix Composites (SiC/SiC CMCs) provided both challenges and opportunities. Since welded thermocouples could not be utilised, non-invasive methods were preferred, also benefitting from the high and stable emissivity of the CMCs under dynamic temperature cycles. As such, the potential to apply an Infra-Red Thermography Camera (IRTC) was investigated within this programme of work, as shown in Fig. 6.

An IRTC operates in a similar manner to a pyrometer, being dependent on emitted radiation from the test specimen (and therefore dependent on surface condition). However, the method offers the opportunity to overcome a significant drawback of both thermocouples and pyrometry, in that only spot measurements can be made, thus precluding further information about the temperature across the entire surface of the volume of material being analysed. Through the use of IRTC however, this can be overcome, since the basic role of an infrared imaging system is to supply information about the temperature map over a body's surface. Additional research detailing the influences of the material in use, emissivity complications, infra-red considerations, size and location of control area as well as other external influences on the accuracy and applicability of the IRTC to control temperature can be found in previous work by Jones [6], with further details about the

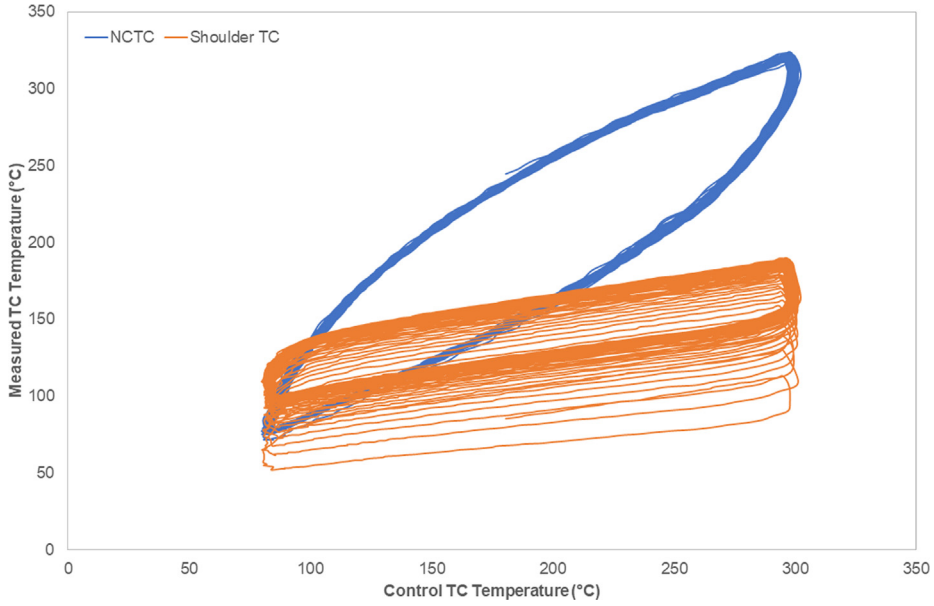

Fig. 2. Thermal profile of NCTC and shoulder TC, show that with time the temperature of the shoulder TC drifts. The NCTC, on the other hand, remains consistent.

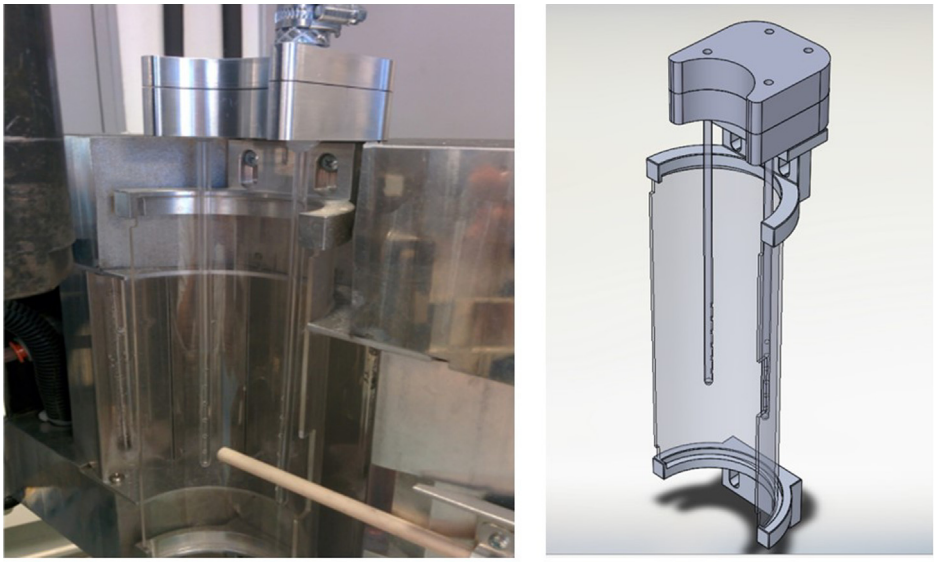

Fig. 3. Bespoke quartz cooling columns employed to deliver uniform cooling across the specimen gauge section (a) image of quartz columns within the radiant lamp furnace and (b) schematic representation of the quartz cooling columns.

operational background and principles reported by Meola [21].

In order to provide the most consistent temperature distribution within a TMF test, it is critical to not only be able to measure the temperature distribution accurately, but also to be able to alter parameters easily in order to improve the profile. Therefore, a specifically designed radiant lamp furnace was utilised as a heating method for this study.

The external surface of the lamp furnace was coated black to avoid any reflective complications with the infrared thermography temperature control. The furnace was designed to accommodate both an extensometer and the non-invasive infra-red temperature measurement device through two opposing windows. Three independently controllable heating zones are incorporated into the design, allowing for accurate temperature control and profiling. Built-in internal compressed air specimen cooling was adopted and delivered rapid cooling rates. In this instance, the test programme consisted of two cycle times; 96 s and 99 s for a 550–850 °C cycle applied to SiC/SiC CMC. The final setup is shown in Fig. 7.

2.4. Fatigue crack propagation using induction heating and thermocouple control

2.4.1. Temperature measurement and control

When investigating fatigue, there are two aspects of interest to consider; fatigue crack initiation and fatigue crack growth (FCG). The studies mentioned previously have focused on analysing 'life to first crack' and it has become apparent through a lack of literature that TMF CG, despite being an important aspect to understand, is one that has not been investigated to the same extent. As already expressed, TMF is a complicated phenomenon and in order to successfully conduct TMF tests in aid of component lifing, temperature control and measurement is of paramount importance. However, when considering TMF CG, accurate crack monitoring also becomes of particular importance and thus leads to additional difficulties when testing. As there are no governing

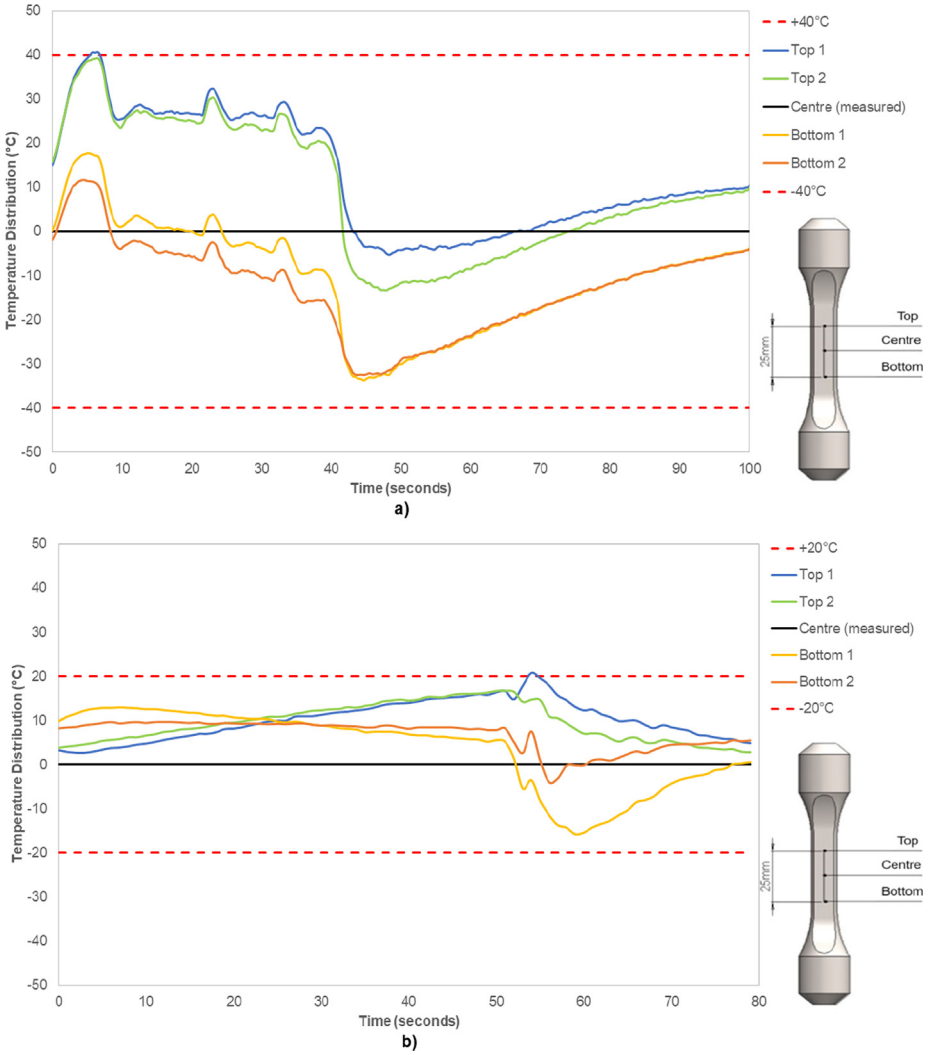

Fig. 4. (a) Initial thermal profile achieved with top-down cooling provided by the Exair air amplifier, showing a large temperature gradient between the top and bottom of the specimen and (b) thermal profile achieved with the quartz cooling channels.

standards or code of practice currently available for TMF CG testing, it is important to draw on existing knowledge to aid the development of such documents and test techniques.

Studies conducted in the early 1980's utilised optical techniques as a method of crack monitoring [22–24] whilst the late 1980's saw a shift towards the use of direct current potential drop (DCPD) as an approach for monitoring crack growth [24–26]. Representing one of the possibilities to measure crack length during experimental FCG investigations, the DCPD method works on the principle of an occurrence of a discontinuity in a specimen being recorded when a homogeneous

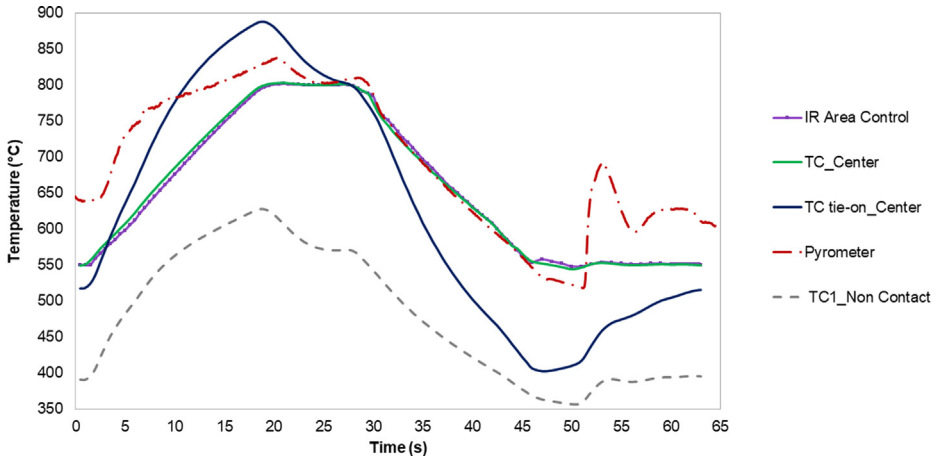

Fig. 5. Dynamic temperature response comparison utilising thermography area control, under RLF furnace heating upon a metallic HE23 coated specimen [6].

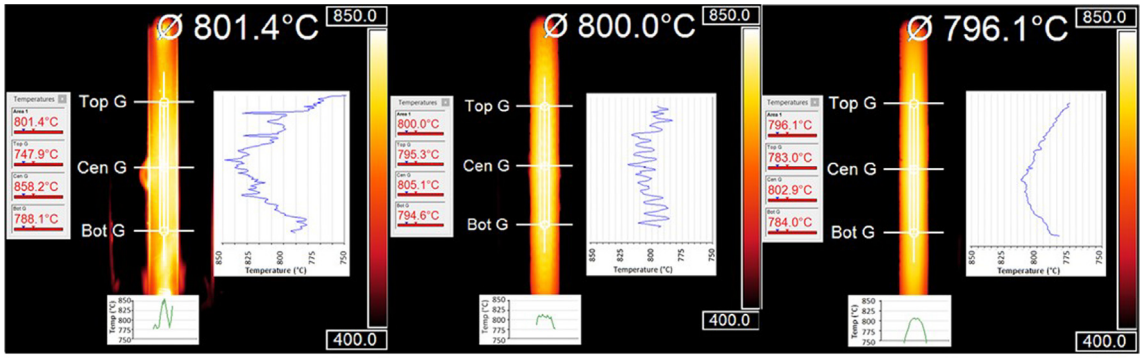

Fig. 6. Thermography view of a dog bone rectangular specimen through a lamp furnace window. (a) Pre-oxidised polished metallic surface (b) Non-metallic uncoated ceramic surface and (c) HE23 thermal paint (TP) coated metallic surface [6].

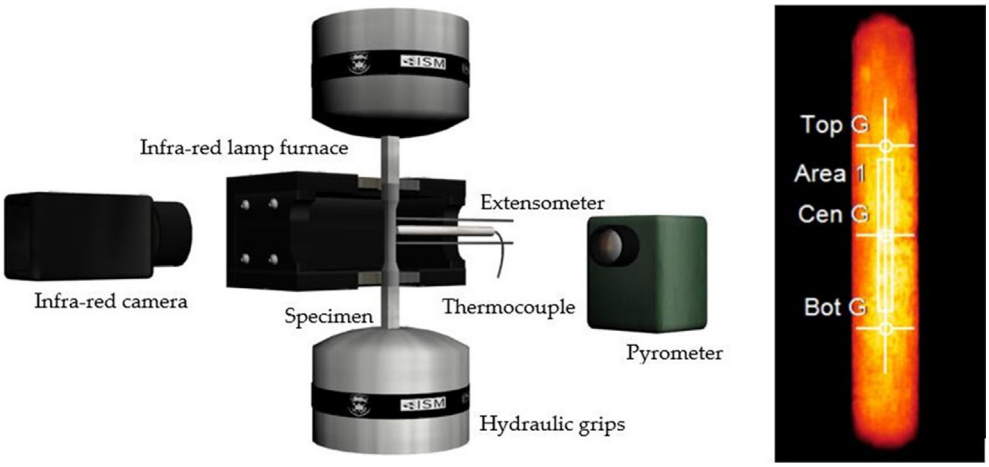

Fig. 7. A schematic illustrating the final setup of the test rig in which a novel quartz lamp furnace with thermography control is adopted [6].

current of an adequate value is passed through the whole cross section of the specimen, causing a potential drop. This method has been widely adopted by governing standards [27] and proven popular in the published literature. However, the method has not been widely investigated under dynamic temperature environments, and therefore this is considered as part of the current work.

The outlined disadvantages of TCs need not be so detrimental in the case of TMF CG testing, since cracks are not freely initiated, developing instead from a discretely machined starter notch. As such, provided an appropriate pre-cracking procedure is applied, crack development from the welded thermocouple location need not occur, and temperature can therefore be directly measured at a location in the centre of the gauge length. The method is recommended by the standards, BS EN 3873:2010 [27] for temperature control and monitoring for FCG of metallic materials. Isothermal standards from corner notch crack propagation specimens state that the TC should have adequate thermal contact to the test piece, 'at the centreline of one face adjacent to the notch, 2–4 mm above or below the crack plane' [27]. Spot-welded type-N TCs were, therefore, used to both monitor and control temperature throughout this study.

As defined in the code of practice for both strain-controlled [1] and force-controlled TMF testing [2], accurate thermal profiling is required to ensure reliable thermal data is produced. Thus, by spot-welding a TC to the centre of each face, as well as ± 2 mm above the crack plane and at similar locations on the adjacent faces, it was possible to obtain an extensive radial thermal profile of the crack plane. Although in TMF CG the main area of interest is that of the crack plane, it was important to ensure an acceptable longitudinal thermal profile was also achieved, thus instead of ± 2 mm, TCs were attached at locations ± 5 mm from the centre TC.

Despite the presence of a pre-existing corner crack, the spot-welded TCs located within the gauge length still proved problematic, resulting in the occurrence of multiple crack initiation sites, as can be seen in Fig. 8. As stated earlier, the spot-welding of TCs to the specimen can create an area of stress concentration and regardless of the pre-existing defect, it is evidenced that caution is still required. This has led to the development of a three stage, load shedding pre-cracking procedure, conducted at room temperature without the presence of TCs. The first stage is conducted at 120% the test load and a frequency of 2 Hz and is reduced to 100% the test load and a frequency of 1 Hz in the final stage. Such a procedure has resulted in TMF CG testing being not only valid but also reliable and repeatable.

2.4.2. Induction coil design

As previously mentioned, ICSs are commonly adopted as a dynamic heating method as they are capable of providing rapid temperature cycles and can be used for complex geometries. However, the importance in coil design has been highlighted by Evans et al [12] and the resultant thermal gradients have been explored by Beck et al [5]. It has also been reported by the same authors that caution is required when combining induction with DCPD since the eddy currents induced by the ICS may interact with the current, creating noise and interference.

Different coil designs have been investigated, with the original preferred design being that shown in Fig. 9a. With such a design, it is possible to load/unload the specimen with minimum disruption to the test setup and thus improves the repeatability. The coil design also

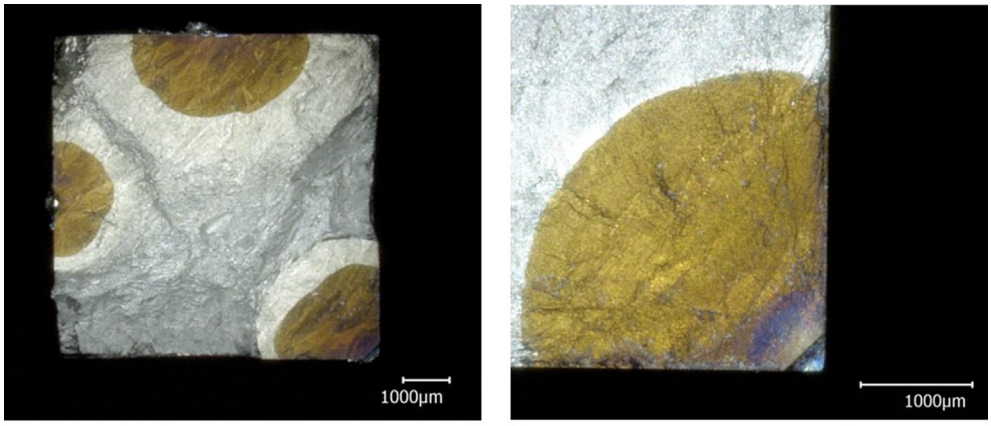

Fig. 8. (a) An optical image displaying the multiple initiation sites caused by welded thermocouples. (b) Pre-cracking is now performed at room temperature, without a thermocouple.

allows for good scope and accessibility to the corner crack and thus it is possible to integrate an infrared camera into the setup. However, through preliminary testing, it became apparent that this coil is in fact not suitable as despite achieving a reasonable temperature distribution, it was also noted that the coil appeared to experience interference with the current, resulting in unreliable temperature recordings.

Reverting to the use of a non-uniform multi-turn longitudinal field helical coil, as shown in Fig. 10a, this eliminated the interference with the current previously experienced and provided a much more uniform thermal profile, as shown in Fig. 10b. With this coil design, it has been possible to achieve a thermal profile that is within the tolerances, outlined in the validated code of practice for stress controlled TMF testing, which states that the temperature at the centre of the gauge section should be controlled with an accuracy of ± 5 °C and the axial temperature gradients within the gauge length should not exceed ± 10 °C [2]. As can be seen in Fig. 10b, the temperature range of the more uniform coil is ~4 °C, unlike that of the previous coil design which displayed a temperature range of ~10 °C, as displayed in Fig. 9b.

Perhaps the most critical issue regarding induction heating for crack propagation testing is the influence of crack tip heating, which has often been seen as a potential drawback of this type of testing [28]. In order to investigate this issue, further use of an IRTC was applied, in order to evaluate the temperature distribution in the region of the crack tip. Measurements were made in an ICS with the crack plane in the test specimen (in this case, RR1000) held at a constant temperature of 700 °C, as measured by a welded N-type TC. Similar measurements have been made for dynamic cycles, however the isothermal case here is presented as it represents the extreme case where power is constantly supplied through the ICS. Fig. 11a shows a thermographic image of the test specimen, and also provides a longitudinal profile of temperature measured graphically. The data provided is taken from a location slightly ahead of the crack tip to avoid interference from the crack section. It is clear that there is a uniformity in the temperature distribution, indicating no effect of crack tip heating.

Nickel based superalloys generally show a thermal conductivity value of $> 10\,W\,m^{-1}\,K^{-1}$. It is useful to compare this with a second alloy system (Ti-6246) which shows a significantly lower value ($7.7\,W\,m^{-1}\,K^{-1}$) to investigate whether heat localises around the crack tip in a material of lower thermal conductivity. Fig. 11b shows a thermographic image of Ti-6246 with the crack plane at 500 °C, and again a longitudinal temperature profile indicates no effect of crack tip heating.

In order to finally optimise the applied waveform, due care and attention must also be paid to the cooling cycle, and in particular the position, velocity and distribution of cooling air that is used. Close control of the cooling method allows for the cooling cycle to be maintained within the desired waveform shape whilst achieving the temperature restrictions defined in the governing TMF standards [1,2]. As

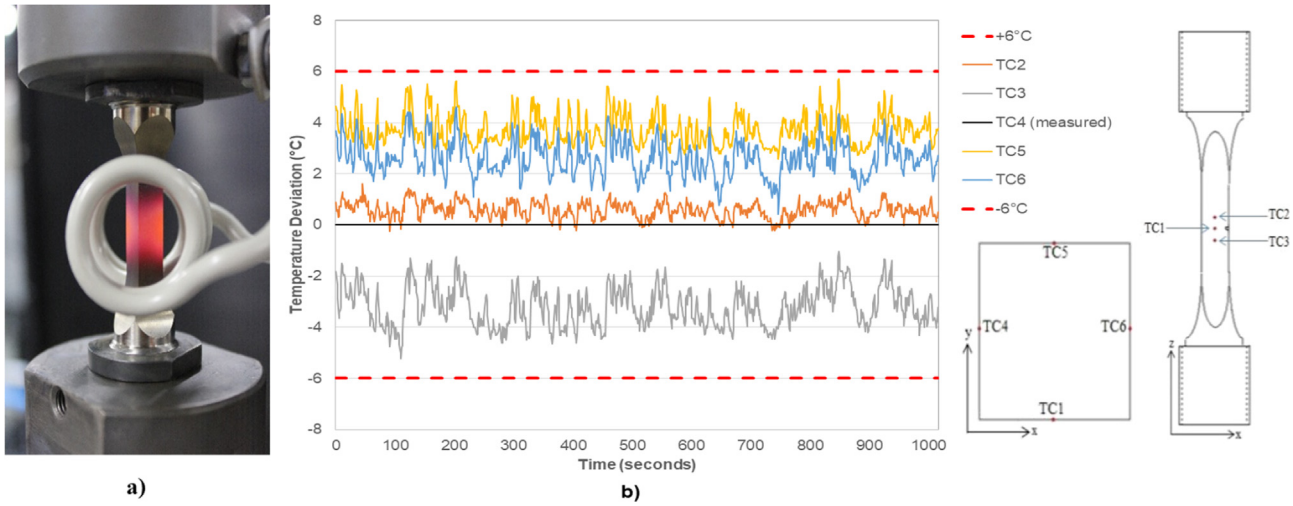

Fig. 9. (a) Transversal field split helical coil (b) Temperature distribution associated with transversal field split helical coil, showing a spread of +/−6 °C in temperature across the critical volume of material around the crack.

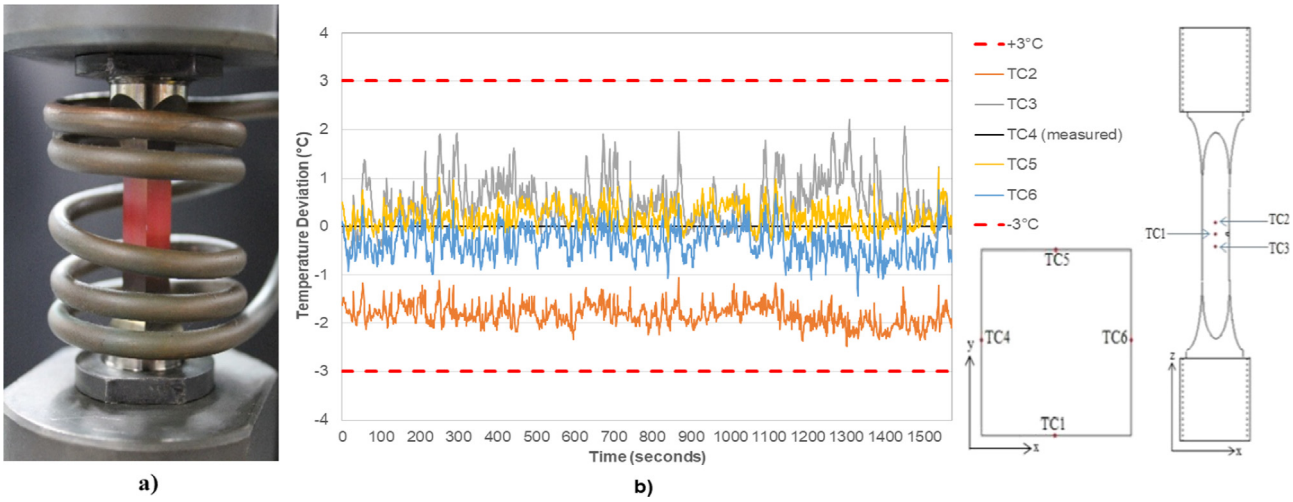

Fig. 10. (a) Non-uniform multi-turn longitudinal field helical coil (b) Temperature distribution associated with non-uniform multi-turn longitudinal field helical coil, showing a spread of +/-3°C in temperature across the critical volume of material around the crack.

such, the current system for TMF CG testing at Swansea employs four Meech air amplifiers situated on a static platform, providing repeatable, reliable and uniform cooling with every test. This setup has been used to test Ti-6246 (200–500 °C) and RR1000 (300–700 °C) under TMF conditions with an overall cycle length of 80 s and 70 s, respectively. The final setup is displayed in Fig. 12.

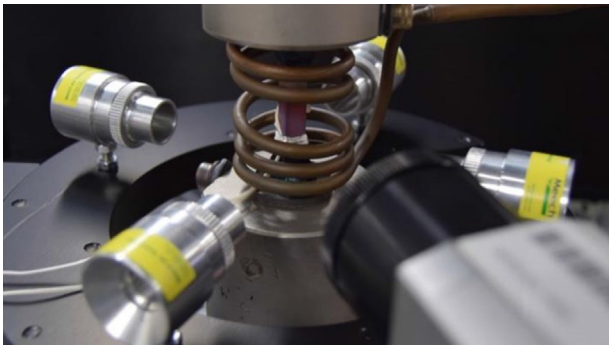

Fig. 12. Final setup utilised for TMF CG testing. As shown, a more uniform induction coil is adopted for the heating and four air amplifiers, situated on a platform, are used for the cooling. Also integrated is an infra-red camera.

3. Discussion

The four rigs developed for TMF research at Swansea University represent state of the art facilities that have evolved to provide consistent, repeatable cycles with greater confidence in the thermal conditions of the critically stressed volume of material than has often been seen in the published literature. This allows for consistent, repeatable results, reducing the scatter often affecting TMF results and therefore allowing for development of theories of micro-mechanical behaviour and constitutive equations to represent TMF life behaviour.

It has become clear during the facility development that there is no single test setup solution that is appropriate for all forms of TMF testing and rather a bespoke approach is required for each set of testing. However, some clear guidelines have become apparent.

Perhaps the most critical development has been the acknowledgement through detailed investigations [7] of the potential inaccuracies involving TCs. Research has shown that shoulder-based TC control shows the potential for significant inaccuracy, and should be considered extremely carefully, and utilised only when alternative techniques are not available. Unfortunately, as described, there is no overriding technique which provides a solution for all test types, but three alternative approaches detailed here can be utilised to employ an

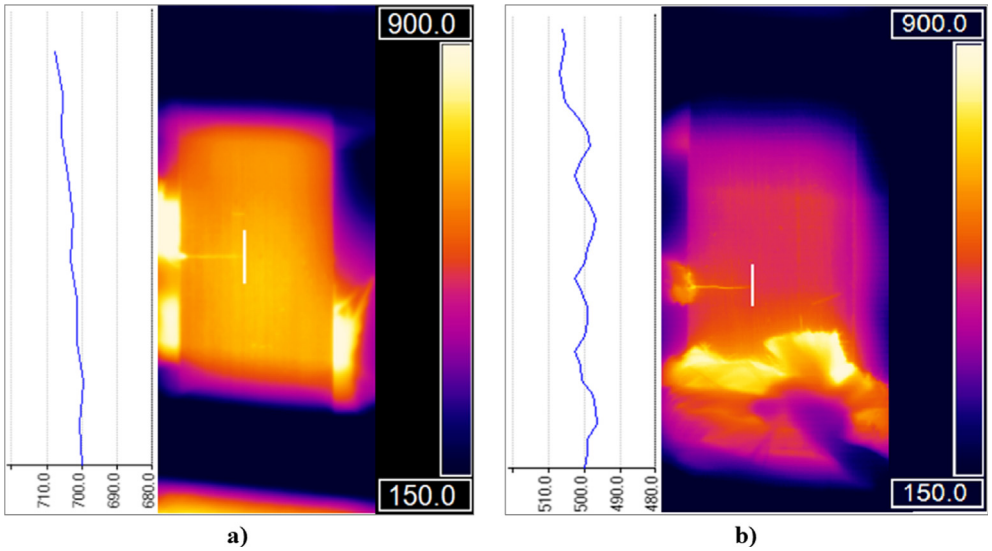

Fig. 11. (a) Thermographic image of RR1000 with crack plane at 700 °C, indicating the fatigue crack growing from the machined notch on the left-hand side of the specimen. The longitudinal profile taken just ahead of the crack tip shows a stable temperature indicating no effect of crack tip heating (b) Comparable thermographic image of Ti-6246 with crack plane at 500 °C. The longitudinal profile again indicates no effect of crack tip heating.

accurate and consistent thermal cycle. The preferred option is thermography control through an IRTC, which can apply area-based measurements and hence provide more information than point measurements gained from pyrometers or TCs, ensuring homogeneity of temperature throughout the critically stressed volume of material. However, as with pyrometry, IRTC measurements are dependent on a stable emissivity value, and therefore require either materials which show no change in surface emissivity throughout testing (as with the CMC materials tested here), or pre-oxidation treatments to stabilise emissivity in metallic specimens. Alternatively, high emissivity thermal paints can be used to stabilise emissivity, however this method has its own drawbacks as discussed by Jones [6,9,19]. The length of these treatments should be minimised however, in case of any detriment to the TMF life. As shown in the case of the testing presented here on CMSX-4, these treatments need to be carefully researched and considered, since not all exposures provide a simple asymptotic curve of emissivity over time. The final method of temperature control considered, by use of a non-contact TC, has provided the most stable thermal cycle of all of the methods employed here, and perhaps offers further opportunities for investigation.

The process by which initial thermal profiling is undertaken should also be considered carefully, since investigations [7] have shown the potential adverse effects of profiling using TCs. Thermocouple shadowing can affect both heating and cooling portions of the TMF cycle, and the consistency of the setup when TCs are removed is highly questionable. Therefore, if available, IRTC methods are preferable for thermal profiling, although similar measurements could be made by pyrometer, although the large number of readings required would make this a more laborious process.

IRTC techniques have also highlighted potential flaws in using highly focussed cooling air channels, leading to cold spots occurring at the specimen surface. Air amplifiers that have been employed in the modernised setups have reduced this effect significantly through a more diffuse flow of air. The amplifiers providing cooling air are also fixed in place using a rigid ring below the specimen, allowing repeatability of positioning for consistent profiles.

As detailed, extensive investigations have been undertaken to evaluate the effect of crack tip heating in an induction coil setup. Measurements using the IRTC have shown no significant effect in either titanium or nickel-based alloys as shown in Fig. 13, and previous work [29] has shown consistent isothermal crack growth rates whether tested under ICS or a conventional radiant furnace. This therefore leads to the conclusion that ICS with DCPD measurements is an appropriate method for TMF CG testing, although care must be taken in pre-cracking of specimens to avoid initiations from welded thermocouples, if this is the preferred method of temperature control in these tests. It is also critical that the appropriate ICS design is used to avoid interference with the PD measurements. Current work is focusing on utilising IRTC as a non-invasive method of controlling temperature and monitoring crack growth simultaneously.

In summary, following the guidelines described in this paper, it has been established through a number of laboratory-based experiments that the use of thermocouples should be carefully monitored, particularly in freely initiating specimens. The lack of consistency from employing a shoulder thermocouple control has led to the development of a non-contact thermocouple solution, which was found to be appropriate. Alternatively, non-contact methods such as pyrometry and thermography control can be considered and are particularly useful in high emissivity materials (such as the ceramic matrix composites described here). In metallic materials, where oxidation is likely to affect surface emissivity values, the appropriate solution proposed was a pre-oxidising heat treatment, although the effects of this were thoroughly considered. Finally, a methodology for TMF crack growth testing was established which has provided consistent and appropriate data, which can be rationalised by comparison with isothermal data in the same material.

4. Conclusions

The current paper has sought to identify and evaluate a range of factors that require careful consideration in developing highly accurate TMF facilities for a range of materials and test types. Possible approaches to TMF testing of a range of high performance materials have been considered, and a number of new approaches introduced, specifically thermography, a non-contact thermocouple and a methodology for TMF crack growth testing.

Through this work, the following guidelines have been identified:

- TMF test setups are by their nature highly bespoke and critically depend on the material to be evaluated, the temperature cycle and the specimen type.
- Remote use of thermocouples at the specimen shoulder for control is a limited methodology, which has shown inconsistencies, along with concerns about the repeatability of thermocouple positioning.

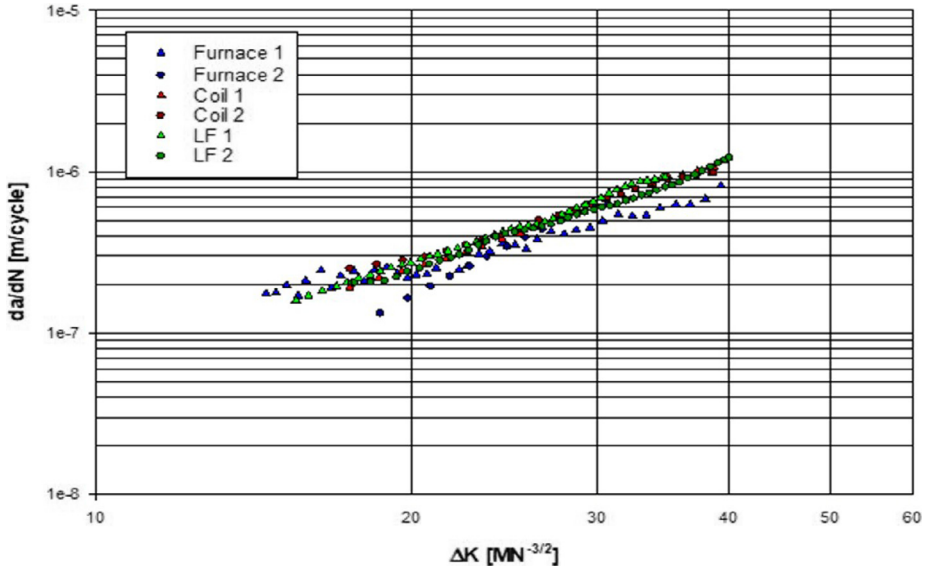

Fig. 13. Graph comparing da/dN vs ΔK of Ti-6246 corner crack specimens tested at the same isothermal conditions, using three different heating methods – ICS, radiant lamp furnace and conventional furnace. Crack growth rates are consistent across heating methods.

- Infra-Red Thermography Cameras (IRTC) provide a major development for TMF testing, allowing for accurate non-invasive area-based measurements. However, for materials where the surface undergoes emissivity variation during the TMF test, it is critical to establish a stable emissivity through pre-oxidation treatments.
- TMF crack growth testing can be undertaken using a DCPD measurement technique under induction heating. No evidence has thus far been found for any effect of crack tip heating.

Author statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the International Journal of Fatigue.

The work presented in this paper was carried out as a collaboration between all authors. The research theme was defined by Mark Whittaker and Robert Lancaster. Jennie Palmer, Mark Whittaker, Jonathan Jones and Robert Lancaster prepared the scientific manuscript, whilst Jennie Palmer, Ashley Dyer, Richard Smith and Jonathan Jones performed the test development mentioned. All authors have contributed to, seen and approved the final manuscript.

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