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An assessment of infrared thermography for cyclic high temperature measurement and control

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Abstract

Infrared thermography (IRT), a non-invasive temperature measurement technique has been investigated and developed for use with cyclic high temperature loading. The technique utilises an infrared thermography camera (IRTC) and Rolls-Royce HE23 black thermal paint (TP). The TP is applied to a test piece surface to provide a stable emissivity value and accurate temperature measurement for the duration of thermal cycling. Spot welded type N thermocouples (NTCs) are utilised for accuracy validation of the IRTC technique for both temperature monitoring and temperature control. An evaluation of the technique has been employed upon diverse test specimen geometries and alloy compositions at temperatures between 100 and 700°C. Unfavourable effects during cyclic temperature measurement such as thermocouple shadowing are also highlighted and quantified. In combination with HE23 TP, IRTC control and measurement has proven accurate to within ±2°C NTCs, a validated cyclic high temperature measurement technique.

Keywords: infrared, thermography, cyclic temperature, emissivity, thermal paint, temperature control

1. Introduction

In recent years it has become more prevalent to assess aerospace and other high temperature materials under cyclic temperatures as they are understood to be more damaging than isothermal conditions. The deformation and damage seen in real components is often better represented by these dynamic temperature loading cycles. As an example, cyclic high temperature testing delivers invaluable insights into the behaviour of high performance aerospace alloys under the extreme conditions typically found inside an aero gas turbine engine. This accurate temperature and loading control during these dynamic cycles is imperative, as they enable the desired phasing between temperature and load, known as the phase angle to be realised, allowing reliable results to be derived for component lifing interpretation.

The publication of the ASTM E2368-10 [1] and more recently ISO12111:2012 [2] strain controlled thermo-mechanical fatigue standards, emphasises the significance of dynamic temperature effects on material fatigue behaviour. However, uncertainty still remains with regards to how accurately temperature can be measured and controlled. When considering data scatter, it is critical not to neglect temperature accuracy [3][4][5][6][7]. Reliable test results can only be accomplished provided that temperature has been kept to within good temperature tolerances ($\pm$ 5°C or $\pm$ 1% ΔT circumferentially at the centre gauge location and $\pm$ 10°C or $\pm$ 2% ΔT axially) as recommended and emphasised by these standards [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). This technique however is not appropriate for rapid dynamic thermal cycles as the heating and cooling rates generated by the furnace are too slow to cope with the dynamic temperature rates required.

In the aerospace industry, temperature ramp rates for dynamic cycles are often based on an engine flight cycle, combining take-off, climb, cruise and descent in a single test cycle. The test cycle is accelerated so that testing ramp rates in real time may exceed +/-10°C/sec. The rapid temperatures required for these tests requires a special type of furnace to be employed, such as radiant lamp furnaces (RLF) or induction coil systems (ICS) which offer this capability. RLF and ICS heat sources are attractive as they can be easily adapted to fit to the frame of existing test machines, therefore they enable the use of established fixtures and specimen geometries, leading to direct comparisons with previous isothermal tests. ICS heating offers a far cheaper and more reliable solution, however a downside to the technique is the homogeneity of the applied temperature is often far less uniform than in a conventional radiant furnace.

Additional complications arise when considering the traditional methods by which temperature is measured and usually controlled under dynamic high temperature cycles. A recommendation is that temperature control may be carried out using spot welded thermocouples (TCs) at the specimen shoulder (or still in the parallel length, but outside the gauge section) for heating and cooling rates up to 10°C/s [2]. The authors have found the accuracy and practicality of such a technique under rapid dynamic thermal cycles to be questionable, particularly in specimens with a long parallel gauge section, where large distances exist between the material under investigation (between the extensometer arms in a strain controlled tests) and the TC location on the test piece shoulder.

Thermocouples have known limitations; the correct type must be selected according to the temperature range under investigation to ensure accuracy[3][8]. Temperature errors can also arise from increasing absorption coefficients of the oxidising test-piece, and via heat conduction through the TC wires giving rise to cold spots[3][9]. Cracks are known to initiate from the TC contact point especially if the TC has been spot welded to the specimen surface [2]. The spot-weld essentially acts as a surface defect, which in turn acts as a stress raiser resulting in crack initiation[10] [11].

Ensuring the TC wire diameter is as small as possible, using individual and not beaded TCs and providing additional thermal contact by wrapping TC wire around the test piece are all measures that can be taken to minimise the severity of the technique [9]. However despite all these measures, spot-welded TCs will induce a cold-spot, hence a surface defect and a resulting crack initiation site [3]. It is therefore not recommended that TCs be spot welded in the test piece gauge section [2].

Direct temperature measurement or control can be achieved from the test-piece gauge section without inducing surface defects using ribbon type TCs. However if this technique is to be employed then adequate thermal contact between the test-piece and TC must be maintained throughout the entire test. Additionally, caution must be taken to ensure the contact does not degrade during cycling as a result of oxidation and or surface roughening [3][8][9].

Another alternative approach is Co-axial TCs. This style of TC arrangement requires holes to be machined into the test-piece surface to allow insertion of the TC. Dynamic temperature accuracy is dependent on the machined hole diameter, as the closer to the TC diameter is to that of the hole, the more accurate the reading will become [9]. However despite the upmost diligence this technique still proves challenging [8]. A further method of TC control involves spot-welding TCs to the adjacent shoulders of the specimen provided the heating and cooling rates are ≤ 10°C/s[2] [3][8][9] reducing the applicability of the technique for cyclic high temperature testing.

An alternative approach is the use of pyrometers. Pyrometers provide a completely non-invasive method for measuring and/or controlling the temperature of a test piece by measuring the amount of thermal radiation emitted from the surface of the material. Accuracy of the temperature measurement is related to the spot size and position of the pyrometer's focal point. The smallest focal point possible is required to obtain the most accurate temperature measurements, since any angular deflection of the beam from the surface of the specimen may result in measurement inaccuracy. Additionally the spectral range of the pyrometer must surpass the T_{min} and T_{max} of the desired temperatures as inaccuracies become apparent within close proximity to the pyrometer's temperature range capabilities [8].

Pyrometers and TCs share a similar limitation. Both techniques can only measure the small area they encompass, typically around $2mm^2$. In addition, pyrometers require thermal profiling using TCs, hence despite being a non-invasive technique and avoiding complications with TC shadowing (discussed further in section 4.5) during testing, inherent temperature errors have already been brought forward from the thermal profiling procedure using TCs.

However the use of pyrometers for dynamic temperature control is not recommended by the relevant standards involved with cyclic high temperature testing [2] as they are sensitive to progressive oxidation causing changes to the surface condition [9]. Depending on the specific temperature and wavelength, the energy radiated by a metallic surface is highly sensitive to any change in the surface condition and therefore is directly proportional to the spectral emissivity of the object [3]. Without a stable emissivity value it is extremely difficult to achieve accurate temperature measurement with a non-invasive technique such as a pyrometer [9][12].

A solution to this is to pre-oxidise the specimen in order to produce a stable oxide layer and hence stable surface emissivity [13]. However, pre-heat treatments and thus consistent oxide formation has previously been found to lack repeatability. Previous work has found the surface emissivity evolution with temperature is dependent on the material, surface preparation, thermal treatment, and the chemical reactions on the surface [14]. Further work suggests there is no conclusive trend of emissivity observed as a function of oxidation time (15±60 min) at a given oxidation temperature [15].

However, provided a stable oxide layer and thus a constant surface emissivity can be achieved, the high temperature pre-exposure and the resultant oxide formation can influence the fatigue life of the test piece [16]. A reduction in fatigue life occurs for some alloys subjected to pre-test temperatures ≥ 500°C [17]. The reductions in fatigue life can be a direct result from surface oxide scale cracking in combination with increased crack growth rates resulting from an enhanced susceptibility to intergranular cracking [17] [18]. This effect was investigated on two Ni-base superalloys in the temperature range 650-704°C for exposures of 100 to ≥ 1000h [17]. The investigation concluded that pre exposure increased scatter in the results and reduced fatigue life by up to 70% compared to unexposed specimens.

In summary, an entirely new non-invasive technique is required that encompasses the complete test setup from thermal profiling to the actual test, that can be used with rapid dynamic temperature cycling for measurement and control purposes. The technique must avoid complications with emissivity inconsistencies and TC shadowing whilst acquiring temperature readings from the specimen gauge section with the utmost accuracy. Additional desirable benefits include an all-encompassing gauge section profiling ability at a less arduous and time consuming pace than currently employed profiling techniques.

An infrared thermography camera (IRTC) has the ability to monitor and control temperature over the entire test piece, rather than a small single spot such as a pyrometer or TC. The current paper seeks to document attempts to implement the IRTC technique for temperature monitoring and control purposes. The technique is used in combination with Rolls-Royce HE23 thermal paint (TP) to stabilise emissivity and highlight the benefits of both a known emissivity and accurate control of temperature over a larger region of the test piece.

2. Description of apparatus

In this investigation two separate testing systems have been utilised. The first system consists of an MTS 250kN Landmark™ servo-hydraulic load frame, where heat is applied via a radiant lamp furnace (RLF), modified and supplied by Severn Thermal Solutions. The second system comprised of an MTS 100kN Landmark™ servo-hydraulic load frame, on which an induction coil (IC) was mounted to apply heating. Test piece temperature is initially measured via type N thermocouples (NTCs) providing a feedback signal to a PID Eurotherm temperature controller. Test piece temperature is monitored and compared using an infrared thermography camera (IRTC). Temperature measurement was then reversed, using the IRTC as the control providing a feedback signal and monitored by the type N thermocouples. The testing systems are shown in Fig.1, and described in additional detail in the following sections.

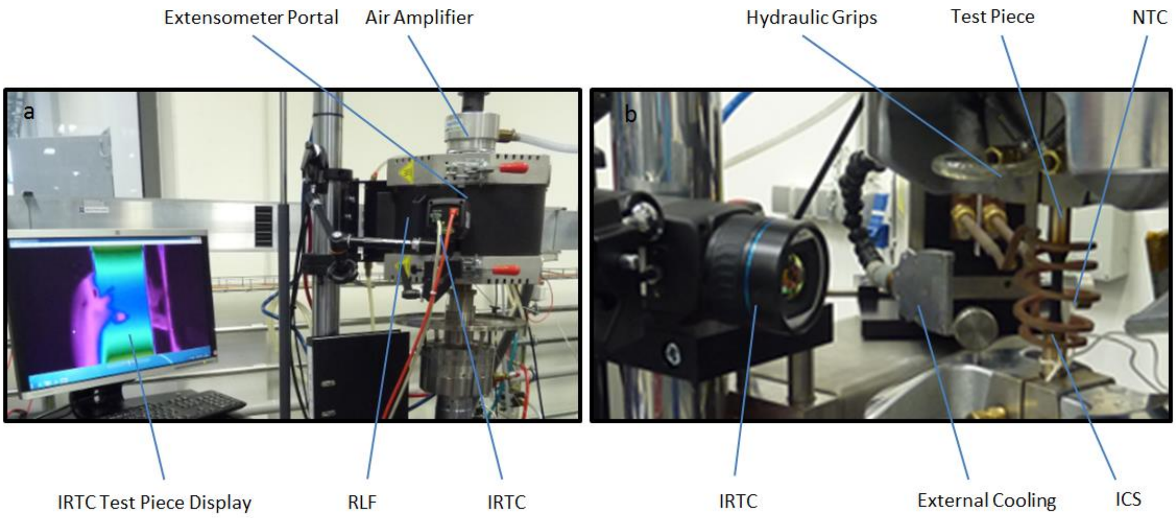

Figure 1. *The two temperature measurement and furnace configurations used; a) RLF with the Flir 655C IRTC. b) ICS with the Flir 655C IRTC.*

2.1 Heating systems

The 12kW RLF (model number RHS2117) has been tailored for this application and supplied by Severn Thermal Solutions. The furnace comprises of two longitudinally divided half cylinders hinged at the centre, with each half containing six lamps. The twelve high-power, vertically mounted quartz lamps heat the specimen to the test temperature. Behind each lamp is a parabolic reflector, which focuses the radiant light towards the centre of the furnace. The IRTC was mounted on the front of the RLF, positioned to image the specimen through the extensometer portal, Fig.1a.

Induction heating allows for rapid heating and cooling rates and can be used with a range of specimen designs and materials. A Trueheat 10kW IC heater delivers an effective method of heating the test specimen to temperatures up 1200°C, depending on the material and specimen geometry. Metallic materials are heated directly with accurate tailored design of the ICS ensuring localised and uniform heating over the entire gauge section of the test piece. This system enabled an IRTC to be mounted in various positions around the test piece to enabling a 360° view of both heating and cooling effects upon the test piece Fig.1b.

2.2 Measurement and control

Test piece temperature is measured by three NTCs along the gauge section ensuring a uniform and steady heat distribution throughout testing. Thermocouples were chosen as a baseline temperature reading based on low cost and simplicity of use as well as being the most widely accepted measurement method in most mechanical testing standards. Furthermore, the use of thermocouples does not require the spectral emissivity of test materials to be defined. The NTCs are used to measure temperature at the test piece surface from the upper, lower and centre locations of the gauge section. These temperatures are used to validate measurements taken from a FLIR SC655 IRTC at the same locations upon the test piece, discussed in further detail in section 3.2.

2.3 Test specimens

Various test specimens were used in this investigation totalling four specimen geometry and alloy combinations. This included the nickel-base alloys, Nimonic 90 and Udimet 720, since these are the most widely available alloys for components used for high temperature applications. Titanium 6/4 and Stainless Steel alloys were also considered. An abundance of archived test data is available for these alloys, enabling a comparison of the results with previously used temperature control techniques. Examples of the different specimen geometries used to explore the flexibility of the IRTC and its ability to cope with variation in specimen area, shape and any reflection due to the features within are shown in Fig.2.

Figure 2. *The different test piece geometries used in the investigation coated with HE23 TP*

Each of the specimens used in the investigation was prepared identically. One side of the specimen remained in the as-received condition referred to as '*front*', whilst the opposing back face, or '*back',* was coated with HE23 thermal paint (TP). The HE23 TP was applied to maintain a stable surface emissivity upon the specimen surface for the duration of testing and is described in more detail in Section 2.4.

Prior to coating with TP, some of the specimen surfaces were lightly grit-blasted with 120/220 grit to slightly roughen the surface in order to improve the bond between the specimen surface and the TP as described in previous work [19]. A conventional air spray gun was used to apply the paint to a thickness of approximately 20-25µm. The paint was then dried in air and cured in a furnace at 300°C for 1 hour. A SEM image of the thickness of the HE23 TP coating on the surface of a test piece is given in Fig.3.

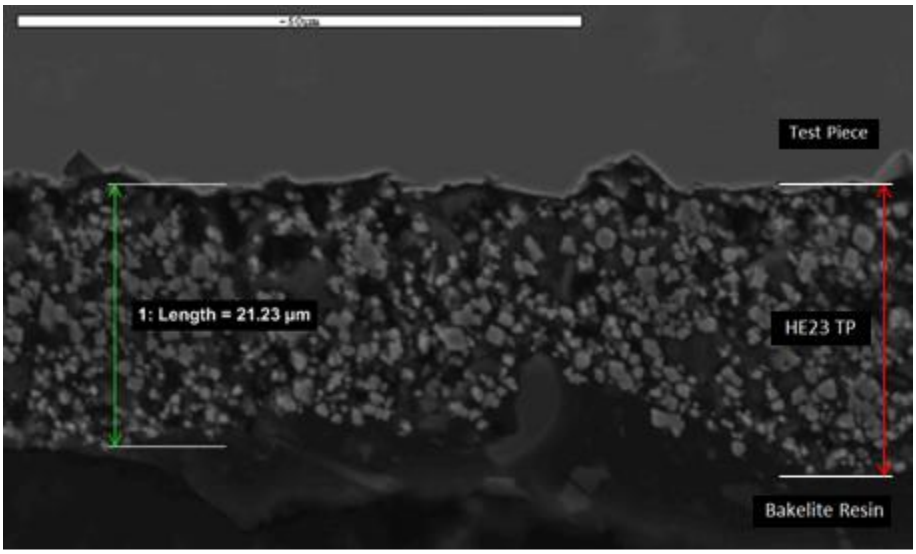

Figure 3. *An SEM image of the HE23 TP coating thickness upon a test piece surface*

2.4 HE23 thermal paint

As previously mentioned, the principal uncertainty within non-invasive temperature measurement techniques such as a pyrometer or IRTC is the emissivity input value to be used from which the temperature can be measured. Techniques used to measure, correct and reduce the influence of emissivity values such as thermal paints (TP) are described in previous work [19].

These paints can be applied to encompass the entire specimen surface as a permanent coating. Alternatively the paint can be applied in a single smaller location or a small spot in order to determine the emissivity by comparing the measured radiance temperature of this spot with that of the uncoated surface [19]. In order to avoid complications and inaccuracies with reflection of radiation from nearby heat sources, such TPs should yield as high an emissivity value as possible, close to the emissivity of a black body, which is rated with a value of 1 [8].

Rolls-Royce plc has developed a variety of exclusive thermal indicating paints and high emissivity thermal paints, for use with gas turbine engine development. These indicating paints display an array of permanent colour changes in proportion with the temperature they are exposed to, and typically encompass a temperature range of 140-1330°C [19]. A description of the practical measurement of reference paint emissivity is also provided [20].
The emissivity of the HE23 TP was found to be stable over a wide temperature range up to 1300°C using pyrometers, Fig.4. This consistency persists over a range of incidence angles due its high stability and lower angular dependency on emissivity, [19]. In summary HE23 TP can deliver an effectively constant, very high emissivity value across an extremely wide temperature range. The paint has the potential to prove invaluable, delivering accurate temperature measurement over an extensive range of both high and low temperatures under non-invasive techniques [19].

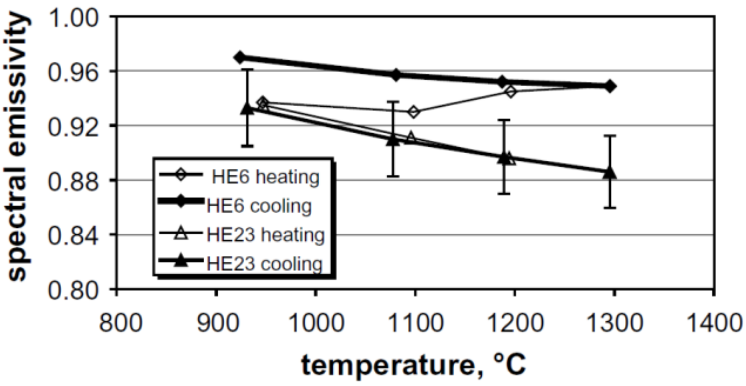

Figure 4. *Normal spectral emissivity of TP HE6 and HE23 measured during first heating and cooling run* [19].

The HE23 TP has proven to be effective for applications such as reference coatings, to measure temperature with a radiation thermometer of surfaces with unknown emissivity [19]. The HE23 TP is used in combination with the non-invasive IRTC technique, and is described in this paper to investigate the stability, accuracy and repeatability of the temperature measurement and control in comparison to NTCs.

3. Experimental Procedure

3.1. Thermal cycles

A RLF and an ICS heat source were both used to employ isothermal and cyclic temperature cycles for the purposes of this work called dynamic dwell and dynamic. Fig.5. The dynamic dwell cycle ramps from 100°C to 600°C to 100°C, holding the temperature at every 100°C interval for 3 minutes, then ramping to the next temperature interval. The dynamic thermal cycle used represented a typical gas turbine flight cycle, commonly utilised to test components under cyclic temperature loading. The dynamic cycle employs a 300-615°C temperature range over a 4 minute period. Throughout all the dynamic thermal cycles the response from the IRTC technique was compared to reference NTCs at the same location on the test piece gauge section.

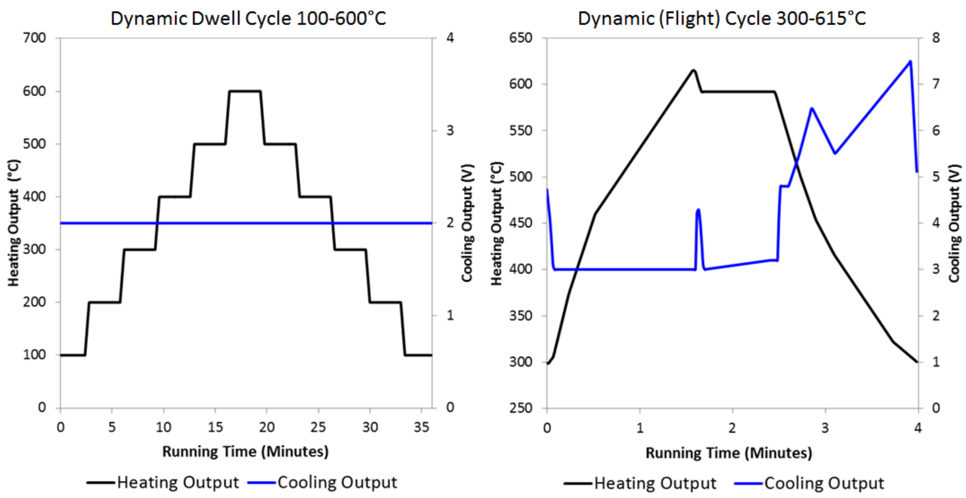

Figure 5. *Thermal cycles used in the investigation for comparisons of temperature measurement techniques.*

3.2. Temperature comparison

To determine the ease of use, accuracy, stability and other benefits of IRTC technique, temperature comparisons were made by an N-type thermocouple (NTC), a known validated temperature measurement technique enabling validation of the results. Temperature comparisons between the techniques were made on a point to point basis; areas of the specimens measured by the non-invasive technique were coated in TP enabling a stable emissivity of the specimen surface to be maintained, whilst NTCs were attached to un-coated areas of the specimen.

Using both techniques to control and monitor temperature alternatively, comparisons could be made between the responses of each. Under the ICS temperature readings were taken from each technique at the centre test piece gauge location (Sp1/TC1), outlined in Fig.6. Using the RLF measurement comparisons were taken at the upper (Sp2/TC2), centre (Sp1/TC1) and lower (SP3/TC3) test piece gauge section locations, as well as the average temperature of the entire gauge section area, Ar1, shown in Fig.7.

During initial trials significant reflection errors were observed using the IRTC under both ICS and RLF heating methods, despite a built in variable input to compensate for the effects. The degree of the inaccuracy caused was found to be dependent on the amount and severity of reflective material within view of the device, typically around 15°C. This was solved by coating the reflective panels inside the RLF with HE23 TP, Fig.7, and hanging a thick black rubber sheet behind the ICS.

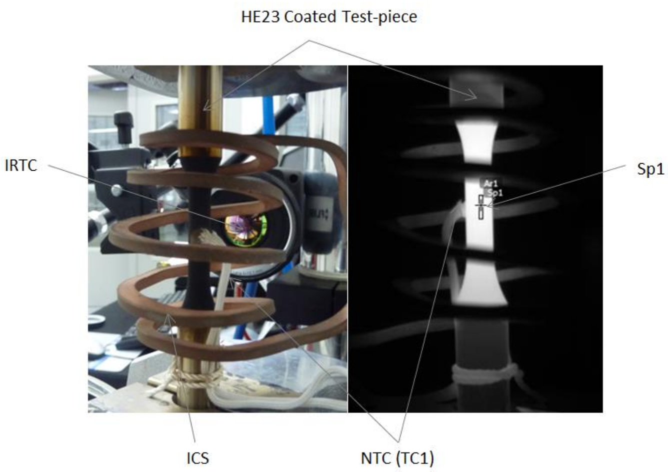

Figure 6. *The temperature measurement comparison set-up, under an ICS heat source, between an NTC and a IRTC.*

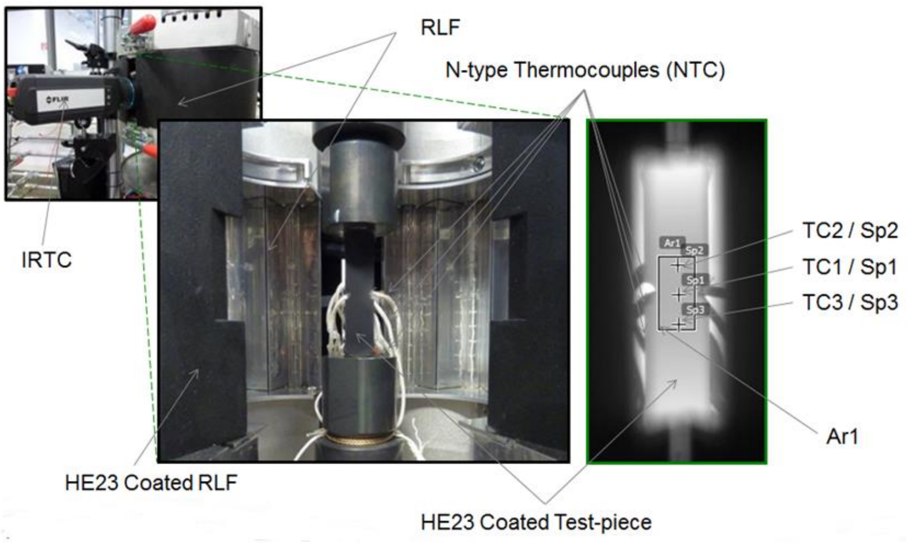

Figure 7. *The temperature measurement comparison set-up, under a RLF heat source, between NTCs and a IRTC.*

4. Results and Discussion

4.1. Emissivity stability of HE23 thermal paint

Isothermal tests were performed to study the accuracy and time dependent effects on the indicated temperature of the IRTC in comparison to NTC control. The investigation was conducted at 50°C intervals between 400-600°C on a Nimonic 90 test piece with no prior oxidation. Specimens were held at each temperature interval for 5 minutes, before values were recorded.

The emissivity input value of the IRTC focused on the test piece was adjusted in order to ensure the same temperature reading was retrieved in comparison to the NTC control, within a tolerance of within ±2°C. To maintain the same temperature reading as the NTC control, the emissivity input value required reducing as the temperature and resultant oxide formation increased with time upon the specimen surface, Fig.8. These results are consistent with those gained by Roebuck et al [12], where large temperature differences were observed between TCs and pyrometers when compared on non-oxidised metal surfaces.

Identically repeating the test with specimens coated with HE23 TP, the emissivity value remained constant throughout the temperature range under ICS and RLF heat sources. The IRTC maintained accuracy to within ±2°C at all temperatures using a constant emissivity input value of 1, Fig.8.

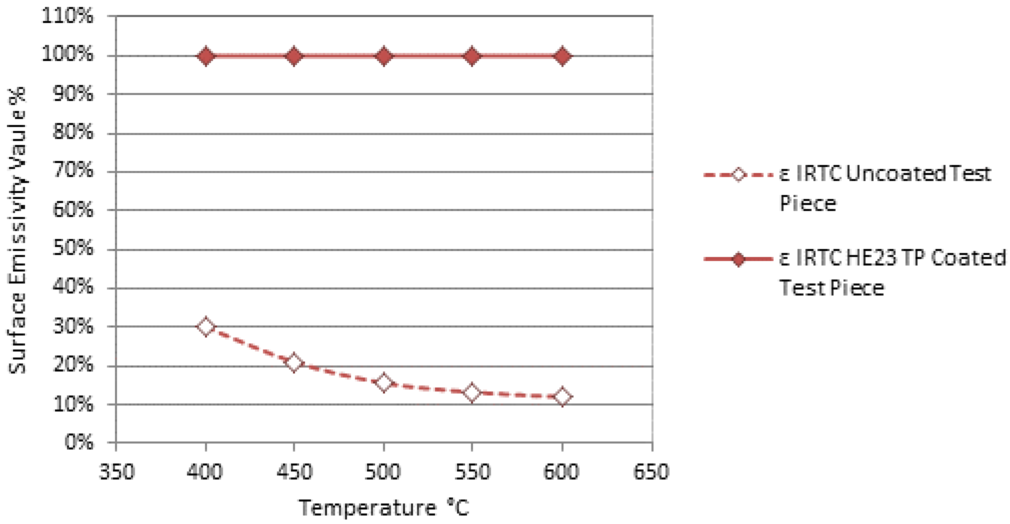

Figure 8. *Emissivity input required to maintain isothermal temperature accuracy under an ICS heat source to within ±2°C of a control NTC when monitoring temperature using an IRTC aimed at HE23 coated and uncoated test pieces.*

To investigate the time dependent effects of degradation at temperature upon the accuracy of the IRTC, a 15 hour 400°C isothermal test was performed on a Nimonic 90 test piece coated in HE23 TP. Measured values from the IRTC were compared to the NTC control at the upper (Sp2/TC1), centre (Sp1/TC1) and lower (Sp3/TC3) locations of the test piece gauge section, defined in section 3.2.

Accuracy was found to be within ±2°C of the NTC at each location for the duration of the test, with no indication of any adverse effects on the HE23 TP coating or accuracy of the non-invasive technique from oxidation. A repeat test was performed for 3 hours to confirm these results post heat treatment. Again measured values from the IRTC aimed at the test piece coated in HE23 TP were accurate to within ±2°C of the NTCs.

4.2. IRTC temperature monitoring accuracy

The IRTC temperature monitoring technique using HE23 TP coated test pieces proved to be accurate to within ±2°C of control NTCs under isothermal conditions. Following these successful trials, several dynamic dwell and dynamic thermal cycles (defined earlier in section 3.1) were performed in order to test the dynamic cycle accuracy. In a similar manner to the isothermal performance, the results prove the IRTC technique is accurate to within ±2°C of the control NTC during dynamic thermal cycling.

Using HE23 TP coated test pieces the accuracy of the IRTC under both ICS and RLF heat sources is almost identical to the NTC control during the heating, cooling and dwell periods of the thermal cycles. When measuring the temperature of non-coated test pieces the accuracy of the IRTC technique reduces considerably due to the absence of the coating. Temperature measurements only remain accurate compared to the NTC control at the temperature at which the emissivity input was calculated, in this case 600°C, outlining the need for the TP coating to maintain a stable emissivity, avoiding fatigue life limiting pre-test heat treatments.

A typical response of the IRTC using both TP coated and uncoated test pieces under an ICS heat source during a dynamic 300-615°C thermal cycle in comparison to NTC control is depicted in Fig.9. The emissivity input values used for the IRTC with the un-coated test piece was 0.16, calibrated during the dwell period of the thermal cycle at the peak temperature of 600°C. The emissivity input value of the IRTC with the HE23 TP coated specimen was 1.

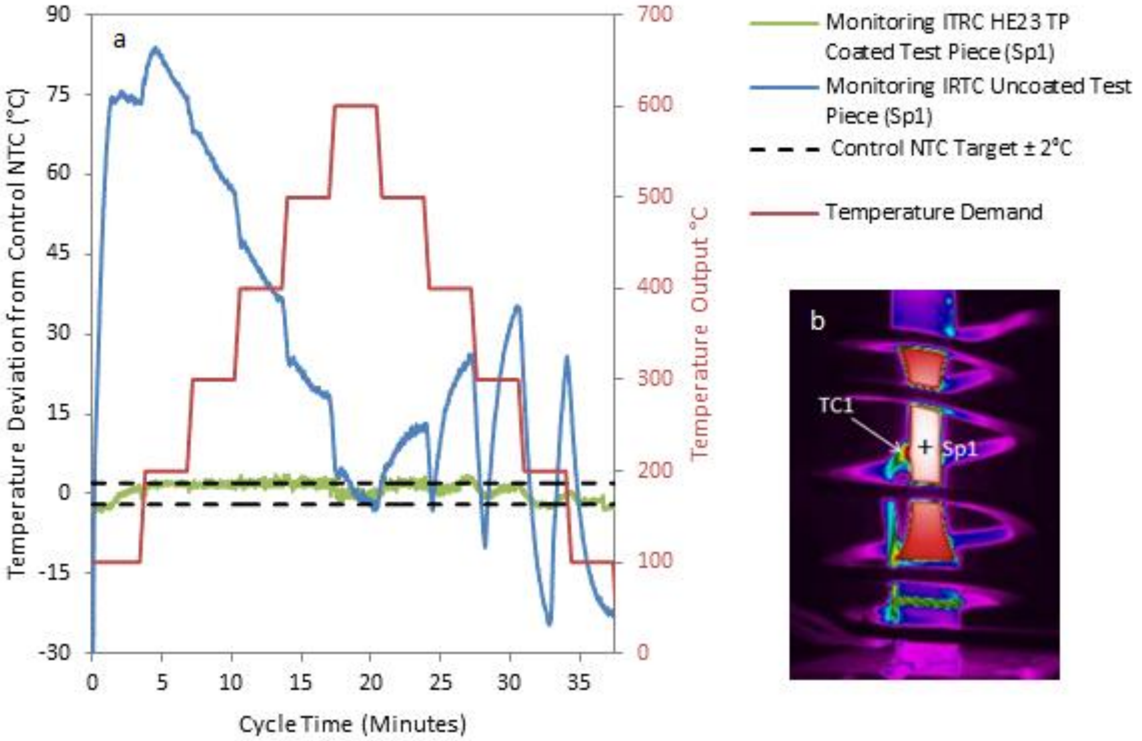

Figure 9**.** *a) Degree of temperature deviation away from NTC temperature control of a monitoring IRTC with both HE23 TP coated and un-coated test-pieces. Comparison is made during a dynamic dwell cycle, under an ICS heat source. The graph includes ±2°C target margins away from the control NTC. b) The corresponding location upon the test piece gauge section at which the comparison was made (Sp1/TC1), centre of the test piece gauge section.*

4.3. IRTC temperature control accuracy

The IRTC was directly connected to the furnace controller input channel forming a closed loop control. The IRTC technique allows multiple methods of temperature control to be used, such as single point and area based control coupled with maximum, minimum and average temperature outputs. To optimise the technique, each of these IRTC control method combinations was utilised and compared to the monitoring NTCs for various alloy and geometry test pieces to find the optimum control method.

Controlling temperature using the single point method, typically from the centre gauge location (Sp1) showed accuracy to within ±2°C of the monitoring NTC during dwell periods of the thermal cycle. This response was also seen when using the area control method, which averages the temperature of the entire test piece gauge section Ar1. The area control method encompassed all three NTCs (TC1, TC2 and TC3) spot welded on the test piece as well as the three IRTC single point measurements (Sp1, Sp2 and Sp3) in the same location. Using this method the entire gauge section was not more than ±2°C of the control NTC during the dwell periods of the dynamic thermal cycles (Fig.10). Using this mode the entire test piece gauge section is controlled whilst specific user defined areas and single points can be monitored (Sp1/Sp2/Sp3). Moreover the feedback from the IRTC allows the entire field of view to be analysed during the test and later for post-test analysis.
However, despite the excellent accuracy in comparison to the monitoring NTCs during dwell periods of the cycle, for the dynamic cycle NTC monitoring temperatures deviated by as much as 22°C during cooling stages and up to 10°C under heating under IRTC Ar1 control on HE23 TP coated test pieces, Fig.10.

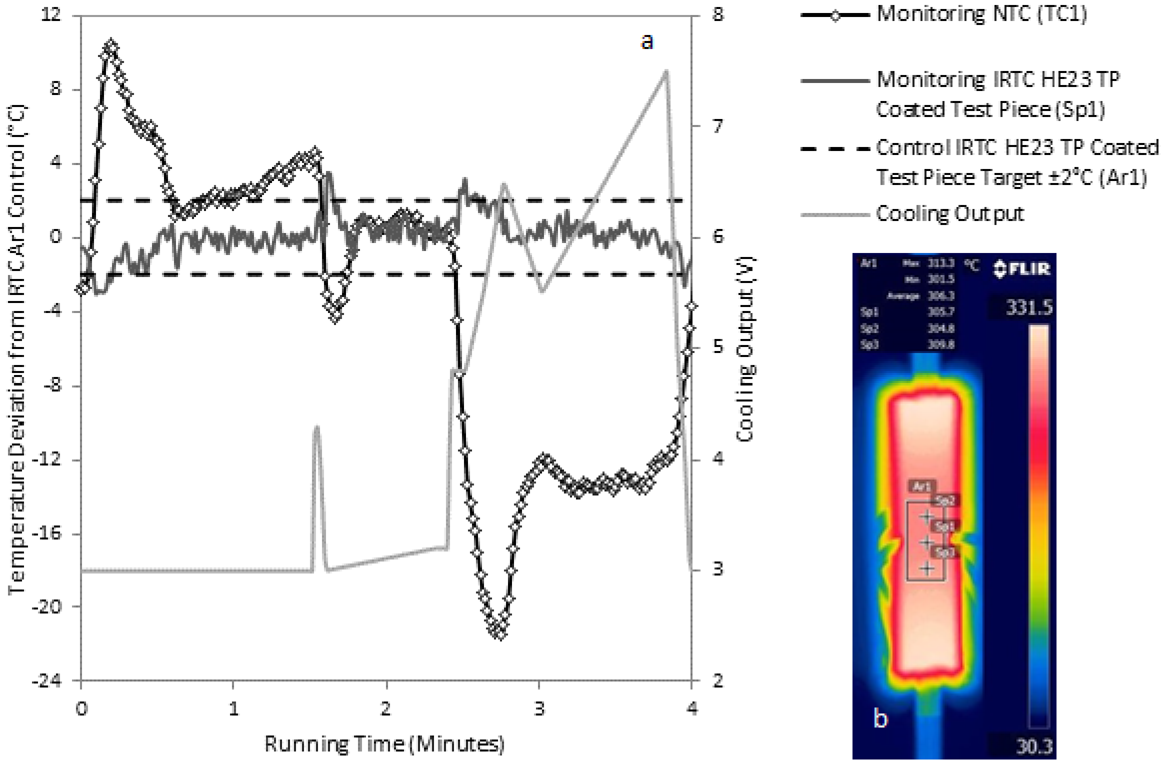

Figure 10. *a) Degree of temperature deviation away from the IRTC average Ar1 temperature control with a HE23 TP coated test piece of monitoring NTCs at the TC1/Sp1 location. The comparison is made during a dynamic cycle, under an RLF heat source. The graph includes ±2°C target margins away from the IRTC average Ar1 control. b) The corresponding location upon the test piece gauge section at which the comparison was made (Sp1/TC1), centre of the test piece gauge section.*

4.4. IRTC Control vs. NTC Control

When controlling temperature using the NTC, the measured response from the IRTC in combination with the HE23 TP coating was accurate to that measured by the NTC throughout the duration of testing. This was observed with both dynamic and dynamic dwell cycles, using both ICS and RLF heating. Temperature deviations remained below ±2°C for the majority of the test, Fig 11a.

Utilising the IRTC as the temperature control method in combination with the HE23 TP coated specimen generated contrasting results in comparison to the NTC monitor. Accuracy to within ±2°C was achieved for the majority of the tests between the IRTC Ar1 control and monitoring NTC, during both dynamic and dynamic dwell cycles. These results were consistent under the ICS and RLF heat sources. Deviations of up to 10°C were found between temperatures recorded during the heating and cooling stages of the dynamic dwell cycle, Fig 11b. The NTC monitor overshot the IRTC control temperature throughout the heating stages of the thermal cycles. A similar trend was found during the cooling stages as the NTC monitor reacts more dramatically to the cooling air, resulting in an increased cooling rate compared to that of the IRTC control. These temperature differences were enhanced during the dynamic cycles with minimum temperatures observed by the NTC monitor of up to 20°C lower during cooling than that of the IRTC control, Fig.10a.

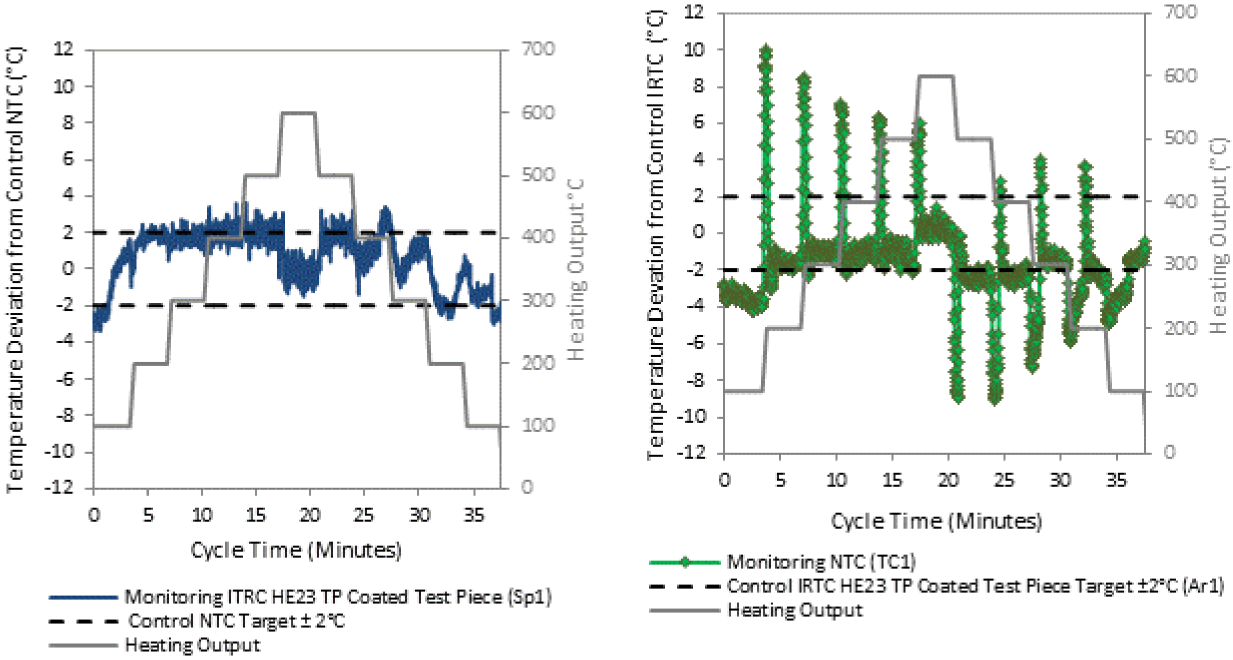

Figure 11. *a) Temperature monitoring response of the IRTC at Sp1 during NTC temperature control from TC1 under a dynamic dwell thermal cycle using RLF heating. b) Temperature monitoring response of an NTC at TC1 during IRTC temperature control over Ar1 under a dynamic dwell thermal cycle using RLF heating. Depicted in both graphs by hashed lines are ±2°C target margins away from the governing control method*

In summary the IRTC can monitor the temperature governed by the NTC control through all stages of thermal cycling. However the same response is not observed when monitoring temperature with the NTC with the IRTC controlling the temperature. The NTC absorbs heat energy during the heating and sheds heat during the cooling stages of the thermal cycle giving rise to different ramp rates and, directly compared to the IRTC, inaccurate temperature readings. The small mass of the thermocouples gives rise to rapid temperature changes, however, in Fig.11a, the response time of the controlling furnace is slower than the time it takes for consistency to be achieved, and hence no deviation is observed.

4.5 Thermocouple shadowing effects

Any object that is close or attached to the surface of the test piece will affect the way it is heated and cooled, this can be termed as 'shadowing' the test piece. Thermocouples with their insulation sleeving shield the test piece from cooling air and trap radiated heat. Cooling air is impeded by the TC reducing its effectiveness in the specific location whilst generating air turbulence around the TC, giving rise to pockets of warmer or cooler air near the specimen surface. These effects can be amplified when using larger diameter TC wires and heavier sheathing.

During thermal profiling of a test piece prior to testing, the majority of the test piece gauge section contains spot welded TCs. For this study, the TCs are applied to the specimen gauge section to establish an accurate thermal response in accordance with governing standards [1][2]. Furnace or coil positions are accurately adjusted, as are the external cooling air jets, to generate the precise thermal profile required [8]. However due to the effects of TC shadowing, the generated thermal profile will be significantly altered once a test piece, with a reduced number of TCs eventually replaces the dummy profile specimen. Without TCs on the specimen gauge section, the effects of heating and cooling will be more direct to the specimen surface.

A flat test piece coated in HE23 TP together with the IRTC was used to quantify the extent of the error that can be generated by TC shadowing. Utilising an ICS heat source, the test piece was heated from 100 to 600°C at 100°C intervals, holding the temperature at each interval for five minutes. External cooling air was then aimed at the test piece from two opposing directions at approximately 180° from each other one with and one without TCs impeding the cooling airflow. Comparisons of the thermal response upon the breadth of the specimen gauge section with and without TCs impeding the external cooling air were made using linear line profiles and point measurements by the IRTC at each 100°C temperature interval.

Similar responses and trends were found at each temperature interval, an example at the 500°C interval is given in Fig.12a, with the corresponding measurement locations shown in Fig.12b. Cooling of the specimen was significantly hindered by the insulated TCs. Results show there is no influence of the cooling air on the temperatures of the gauge section when TCs are present (Linear line profiles Li3 and Li4 Fig.12). The temperature of the gauge section was reduced significantly when cooling air was directed from the opposing direction without TCs impeding the airflow. A substantial decrease in temperature of over 20°C was achieved for both linear profiles Li3 and Li4 (Fig 12). The effect of cooling air from both sides and without TCs is shown in line profile Li2 (Fig 12)

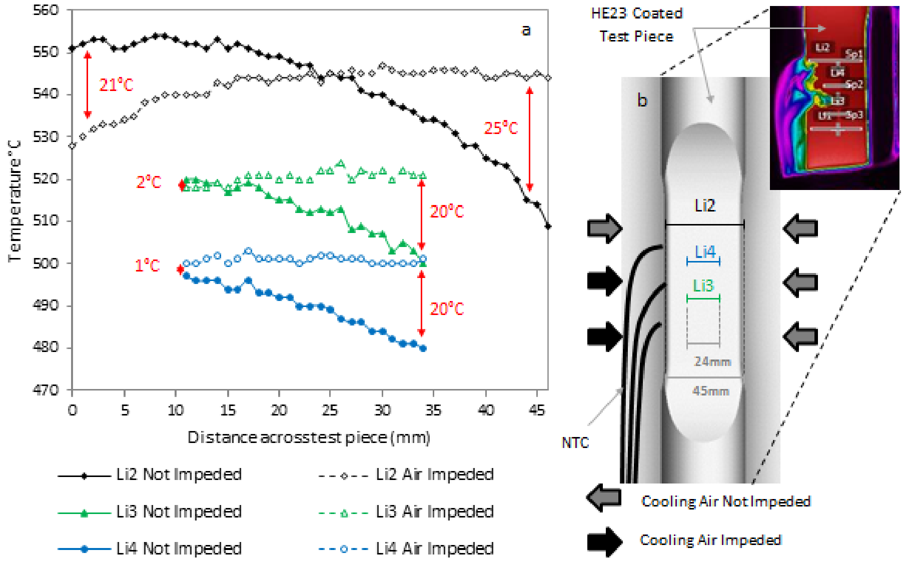

Figure 12. *a) Comparisons of the thermal response across the breadth of the specimen gauge section under ICS heating, measured using the IRTC HE23 TP technique. b) Line profile measurement locations and cooling air flow paths.*

4.6. IRTC temperature control LCF test validation

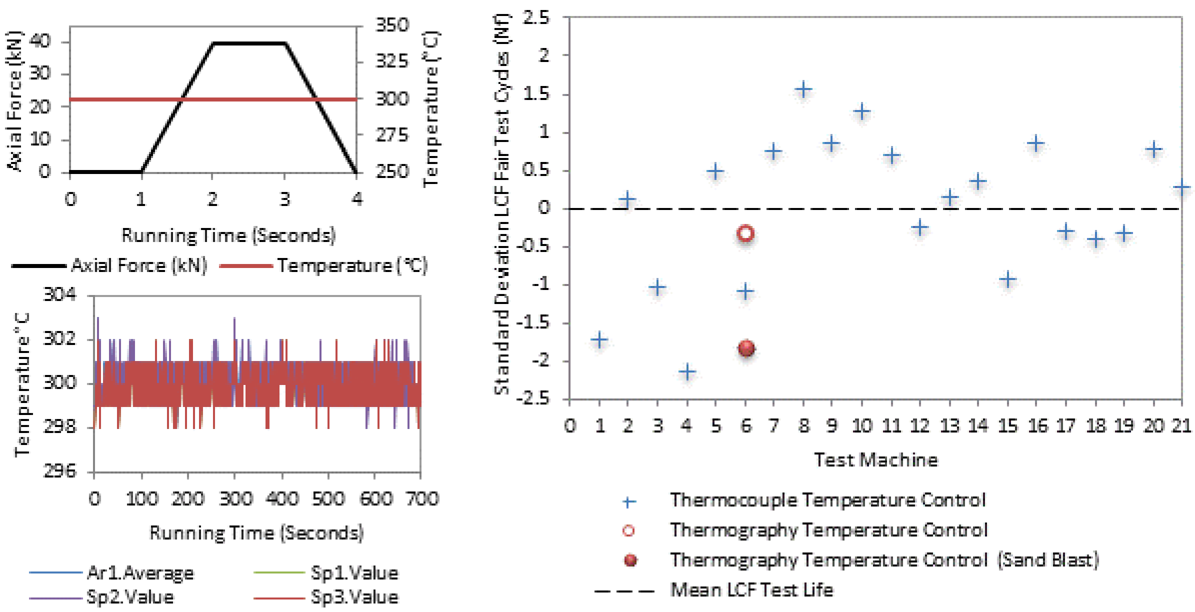

Figure 13. *a) Trapezoidal load waveform and temperature profile used during the LCF fair test. b) Temperature response of the monitoring IRTC Sp1, Sp2, Sp3 and Ar1 locations upon a HE23 TP coated test piece during IRTC average Ar1 area control. c) A scatter plot comparison of all thermocouple temperature controlled Ti6/4 LCF Fair tests at Rolls-Royce MTOC,*

with thermography controlled tests displayed as filled and unfilled circles. Values are compared through standard deviation against the mean value, in this case set to zero.

Investigating the capabilities of the IRTC Ar1 area temperature control technique further, a generic 300°C isothermal 40kN Trapezoidal low cycle fatigue (LCF) test, termed a 'fair test' was carried out under RLF heating to examine any adverse effects of loading on the temperature control method, Fig.13a. A titanium 6/4 fair test specimen was coated in HE23 TP, and the temperature control was governed by the average temperature throughout the specimen gauge section area, Ar1. The area allotted for temperature control was a thin rectangle, vertically aligned along the centre gauge section of the cylindrical specimen.

The results showed no detrimental effects of loading on the temperature accuracy during the test Fig.13b. Moreover, utilising the averaging control method balanced the temperature of the specimen faster and more accurately than observed with TCs. The satisfactory quality of the test result was based on the number of cycles to failure, compared to the scatter of previously performed fair tests (Fig.13c) under the same test conditions.

A repeat test was performed to investigate the effects of shot blasting prior to the application of HE23 TP, to enable enhanced adhesion between the TP coating and the specimen. Again, the temperature accuracy and control during the test did not deviate by more than ±2°C over the entire specimen gauge section. However the resulting life of the specimen was reduced compared to the previous test but still fell within scatter of previous TC controlled fair tests. Fractographic analysis showed shot blasting did however generate defects on the material surface enabling cracks to initiate easily and frequently leading to additional initiation sites and a premature failure life compared to non-shot blasted specimens.

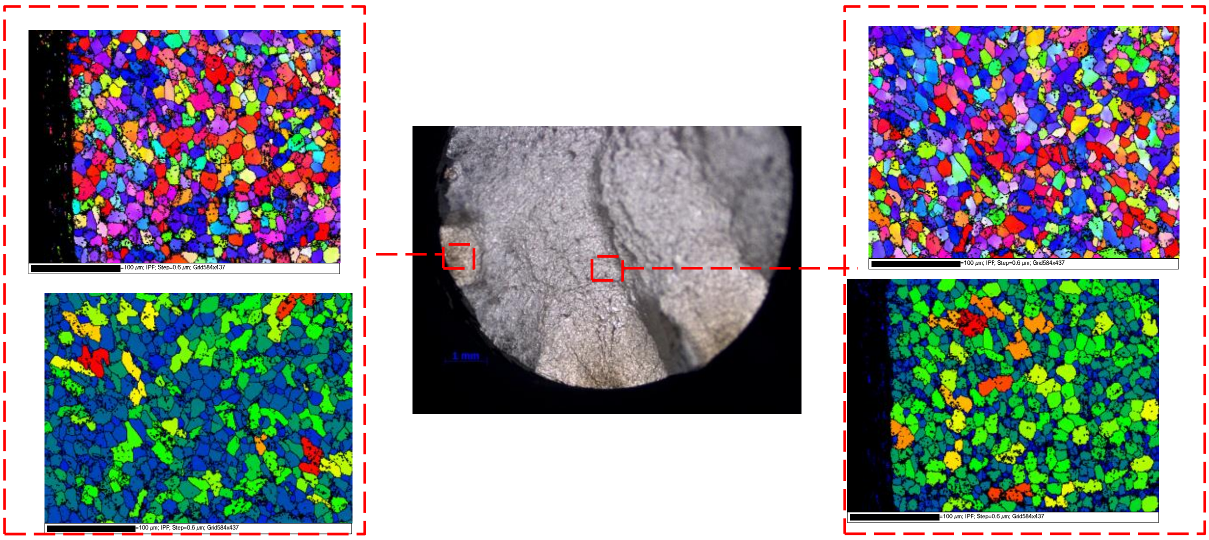

Figure 14. *Macro images of the LCF Ti6/4 fair test specimen fracture surface, failed under IRTC temperature control with no prior shot blasting. Shown are EBSD orientation and internal strain maps of at the surface of the test piece and in the bulk of the material.*

Electron backscatter diffraction (EBSD), a scanning electron microscope (SEM) based microstructural-crystallographic technique, was used to examine the HE23 TP coated fair test specimen post-test. Analysis focused on any indications of adverse effects of the TP coating on the microstructure. Orientation, texture, internal strain and grain size were quantified and compared between the bulk and surface of the material coated in HE23 TP. No significant variations were found between the two locations, as shown in Fig.14.

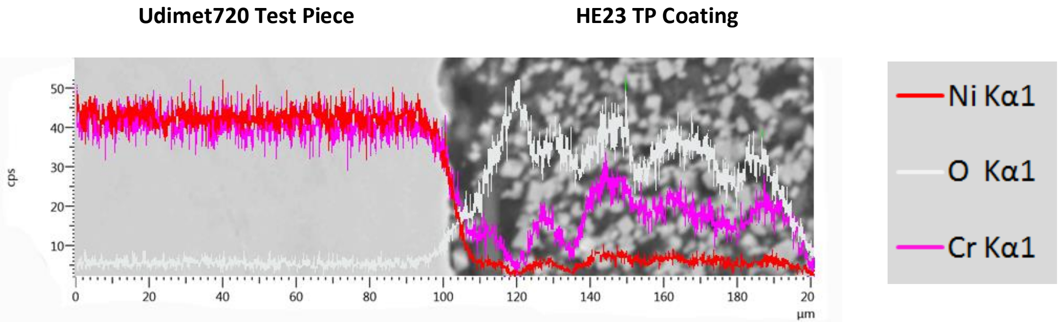

Figure 15. *EDX elemental line scan analysis of the interface between the HE23 TP coating and Udimet720 test piece surface, subjected to thermal cycles a 100-700°C temperature range.*

EDX analysis was performed on a test piece that had been coated in HE23 TP and subjected to numerous thermal cycles in the temperature range 100-700°C. The EDX elemental line scans, at the interface between HE23 TP and Udimet720 test piece surface show no decline of nickel or increase in oxygen at the surface of the specimen, indicating no diffusion had taken place, Fig.15. The paint appears to be acting as an oxidation barrier preventing the test piece from oxidising. Further work is planned to investigate this in more depth.

6. Conclusions

Numerous complications and inaccuracies can be associated with TCs when using rapid heating and cooling rates. Because of this, new technology in the form of an IRTC was considered that would be non-invasive and offers the option to not only monitor temperature but also to control it. The work undertaken in this study has shown that;

- Pyrometers have proven accurate for temperature control and monitoring purposes, provided specimens are heat treated prior to testing to enable the generation of a stable emissivity value of the test piece surface within the experimental study and previous work [13]. Without a stable surface emissivity results can prove inaccurate, as the specimen oxidises and its emissivity alters accordingly [9][12].

- Despite the effectiveness of pre-heat treating to generate a stable emissivity and hence oxide layer [13], the effect of this high temperature pre-exposure and resulting oxide formation on the specimens can be detrimental to the fatigue life of Ni alloys at temperatures ≥ 500°C, deeming the technique undesirable in some cases [17].

- Emissivity readings are the primary cause of inaccuracy when using non-invasive temperature techniques on uncoated test piece surfaces. The HE23 TP provides a stable value of emissivity with both pyrometry and IRTC temperature measurement and control purposes using both ICS and RLF heat sources. Results have shown consistent accuracies to within ±2°C of the NTCs when using the HE23 TP coating in combination with an IRTC or pyrometer. No prior high temperature heat treatment of the specimen is required before the tests can begin.

- The results obtained prove the IRTC is a very promising method for measuring and controlling temperature under both ICS and RLF heat sources. This study has generated significant results when controlling temperature using the IRTC, highlighting inaccuracies associated with TCs such as exceeding cycle maxima and minima.

- TCs have shown to be sensitive to cooling air and as a result display faster cooling rates and apparent lower temperatures than those observed using the IRTC. The TC not only measures the heat from the specimen but also absorbs heat energy heated during the test. As a result faster heating rates are observed with peak temperatures exceeding the target temperature by as much as 10°C. As the IRTC is completely non-invasive and is not affected by the cooling or heating, it has proved an extremely accurate and reliable temperature measurement technique when used in combination with the HE23 TP coating.

- The IRTC can control temperature over the entire test piece gauge section area, rather than a single point which is the only option when using TCs and pyrometers. Averaging the temperature over the entire gauge section generated stable and accurate results from all regions of the gauge section in comparison to monitoring TCs.

In summary the IRTC can accurately measure temperatures when using HE23 TP coated materials. The IRTC is not affected by cooling air or heating devices and does not cause shadowing effects. Profiling and control can be achieved within a rapid setup time and encompasses the entire gauge section generating a significant volume of data that can be analysed live or post testing.

7. Acknowledgements

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