The development of stress controlled thermo-mechanical fatigue testing at the Rolls-Royce Mechanical Test Operations Centre (MTOC), Dahlewitz, Germany.

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Introduction

Thermo-mechanical fatigue (TMF) refers to a form of non-isothermal fatigue in which a material is simultaneously subjected to independently controlled thermal and mechanical loading. Service components such as the turbine disc in a gas turbine engine are typically subjected to TMF during turbine start-up and shut-down. The TMF test makes it possible to closely simulate the service conditions of engineered components within a controlled laboratory environment. It characterises the response of a material to simultaneous cyclic temperature and mechanical loading, producing a synergistic material response which cannot necessarily be predicted using isothermal fatigue testing. The data generated from these tests aids developers model component behaviour as well as to validate existing models.

The difference between stress controlled TMF testing and the more commonly encountered strain controlled TMF testing is that the test is performed under load control or with an applied value of stress, depending on the flexibility of the equipment used. The specimen is additionally designed to represent a feature encountered on the finished part. The stress controlled TMF tests performed at MTOC are intricate and incorporate a combination of temperature-loading phases replicating the service cycle of a component. The specimens are heated using radiant lamp furnaces, combined with an integrated customised compressed air cooling system to control temperature rates.

Temperature control is very critical to accurate TMF testing as the interaction between temperature and mechanical loading affects the fatigue life of the material. Commissioning of the stress controlled TMF testing system therefore initiates with multiple stages of thermal profiling. These establish the temperature distribution across the specimen and in particular ensure that the target temperature path can be maintained throughout the test.

Equipment

The testing system

The testing system consists of an MTS 250kN Landmark™ servo-hydraulic load frame, on which is mounted a 12kW infra-red radiant lamp furnace (model number RHS2117) which has been modified and supplied by *Severn Thermal Solutions* (Figure 1). The radiant lamp furnace uses twelve high power vertically mounted quartz lamps to heat the specimen to the test temperature. The furnace comprises of two longitudinally divided half cylinders hinged at the centre, with each half containing six lamps (Figure 2). Behind each lamp is a parabolic reflector, which focuses the radiant light towards the centre of the furnace. Additionally there are two quartz glass liners positioned to protect the lamps and simultaneously provide a smooth cooling air channel through the furnace (Figure 3). All testing frames participating in the development of this test method at MTOC were fitted with identical radiant lamp furnaces.

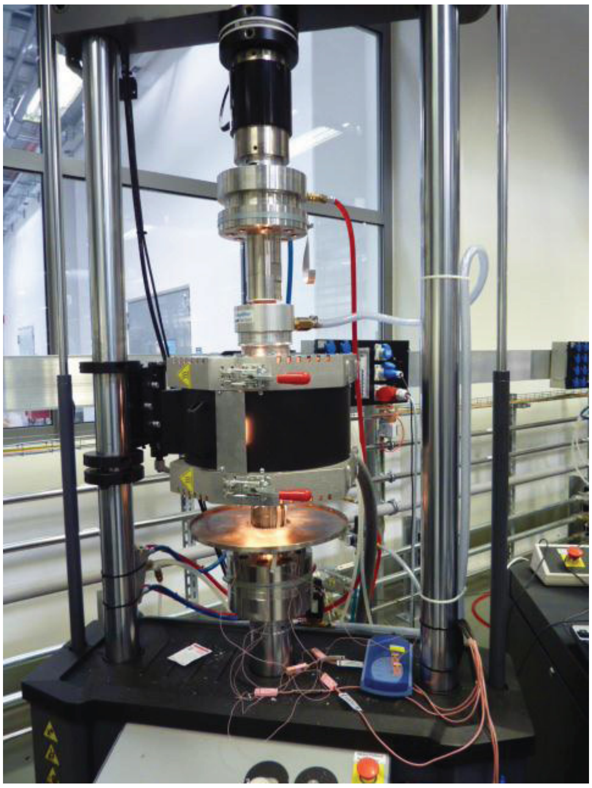

Figure 1: The stress controlled TMF testing system consists of a MTS 250kN *Landmark* load frame, 12kW Infra-red radiant lamp furnace, and facility compressed air cooling additionally accelerated with an *Exair* air amplifier, all controlled by the MTS *TestSuite* software.

The upper and lower loading columns and the furnace are water cooled to a constant 27°C. Above the furnace fitted around the upper loading column is an *Exair* air amplifier (Figure 4). This provides the cooling required in order to attain the rapid change of temperature required for both the heating and cooling phases associated with TMF testing. The air amplifier accelerates the MTOC facility compressed air supply, which during these tests was at 517kPa (75psi), up to approximately $35.4m^3$ per minute (1250 Standard Cubic Feet per Minute).

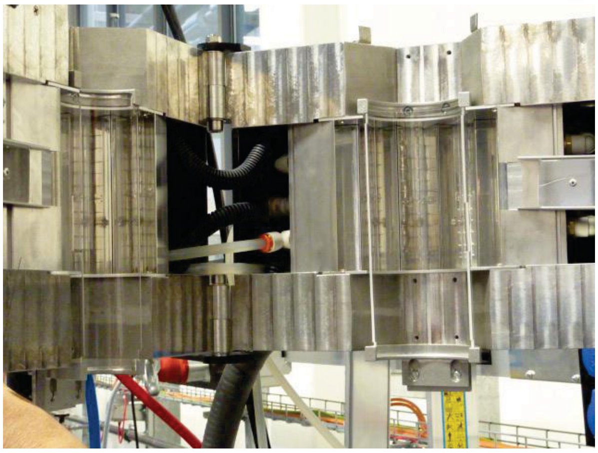

Figure 2: Internal view of the Infra-red 12kW Radiant lamp furnace. 12 vertically mounted lamps provide the rapid heating rates required for this type of test. The quartz glass liners enable the cooling air to pass smoothly through the furnace.

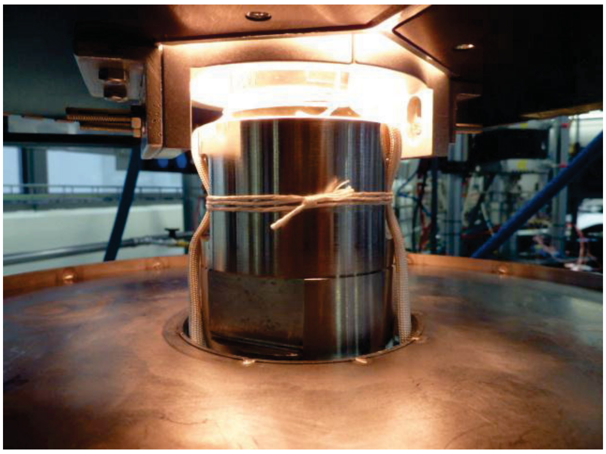

Figure 3: The base of the furnace where the hot air is exhausted. The disc under the furnace dissipates the heat away from the machine. It additionally acts as protection should a part of a hot specimen fall out of the furnace. Centralising brackets are located underneath to ensure accurate positioning of the furnace once it is closed.

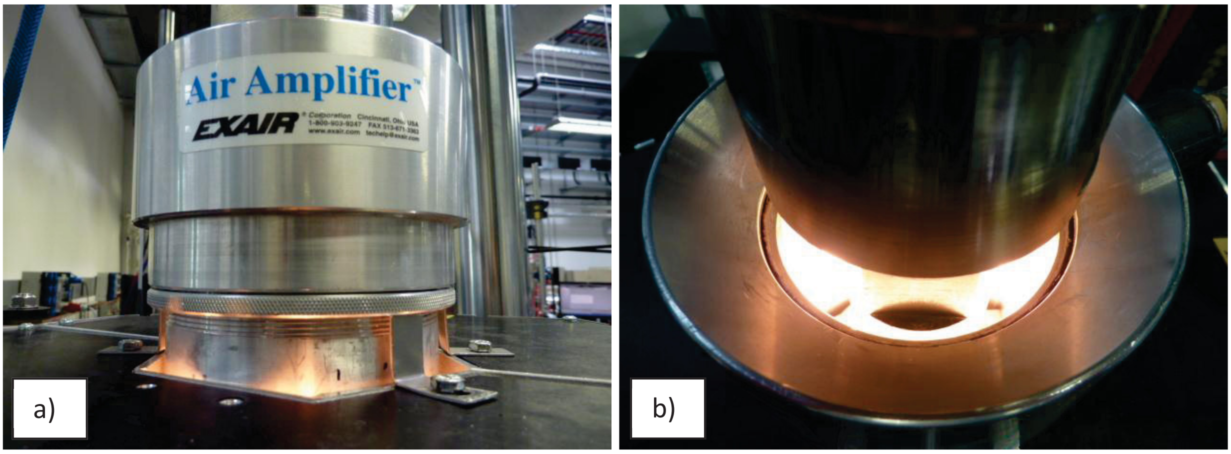

Figure 4: The *Exair* air amplifier, situated at the top of the furnace. a) Centred at the top of the furnace it accelerates MTOC facility compressed air up to 35.4m^3 per minute (1250 SCFM) at 517 kPa (75psi). b) View looking into the top of the furnace at over 400^{o}C.

Specimen design

The development of stress TMF at the Rolls-Royce Mechanical Test Operations Centre (MTOC) was initiated on a wrought nickel disc alloy, Udimet 720Li (REC). The test pieces used are flat and notched at the centre, with the notch geometry representing, for example, a bucket groove feature on a high pressure turbine disc. This alloy and specimen design was chosen because Rolls-Royce had previously commissioned an external test house to test this alloy under stress controlled TMF. It was therefore considered that the data obtained at MTOC could be compared with that of the other test house as a basis for validation.

Thermal profiling – controlling the temperature gradient

Commissioning of the stress TMF testing system begins with thermal profiling. Temperature control is very critical to accurate TMF testing as the type of loading also varies the interaction between temperature and load has an effect on the material's microstructure and subsequently its lifetime. The degree of accuracy must be high, at temperatures above 400°C the allowable deviation tolerances at the gauge section were set at +/-5°C of the target temperature.

The first form of thermal profile, stage 1, consists of a dummy specimen of the same alloy composition and mechanical properties as the test specimens, on which a total of ten 'N' type (0.2mm diameter) thermocouples (TC's) are spot welded at crucial points around the specimen (Figure 5). These thermocouples were covered along their length with glass fibre sleeving to reduce the effect of direct heating of the thermocouple by the radiant lamp furnace. A control TC is spot welded to the top shoulder and a monitor TC is spot welded to the bottom adjacent shoulder. Both these TC's are critical for the test specimen as they will be the only TC's present for the test. The gauge section has eight TC's. The positions of these TC's are such that the thermal gradient of the gauge section can be measured. In conjunction with varying amounts of air cooling and the appropriate amount of heating output, it is possible for the specimen to receive the desired temperature at the gauge section.

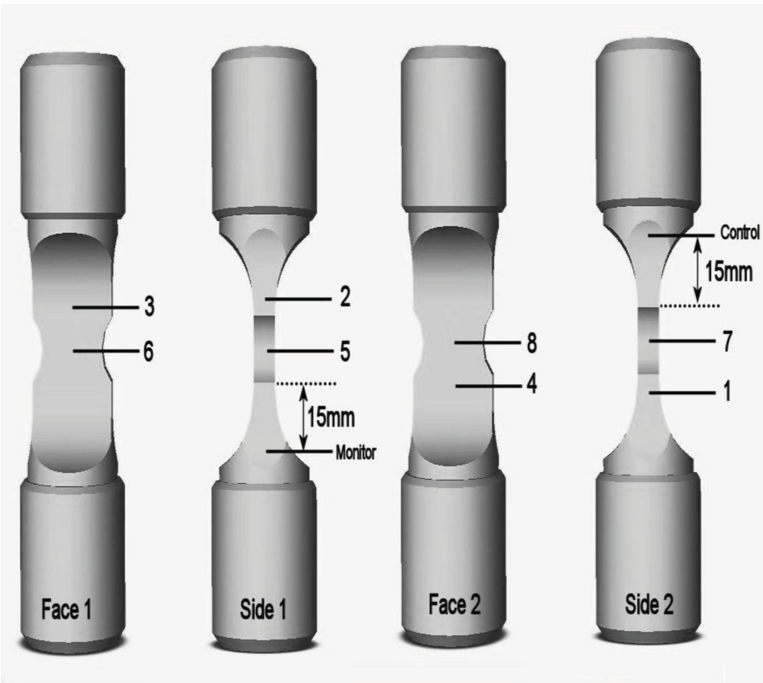

Figure 5: Stage 1 thermal profiling showing thermocouple positions. A total of 10 TC's are spot welded to the specimen surface at positions around the specimen, and control and monitor TC's at the adjacent shoulders.

On completion of Stage 1 thermal profiling, a second profile (stage 2) is performed on the same specimen, now with only a total of six TC's. The four TC's within the gauge section are retained along with the control and monitor TC's the rest are removed (Figure 6). This new profile confirms another issue uniquely seen with radiant lamp furnaces, the effect of 'shadowing'. The upper TC's lay across the specimen surface and, although less than 2mm in diameter (ceramic sleeving enlarges the area of the TC), they create shadows over the specimen. Additionally they block the air cooling from reaching the specimen surface and create some turbulence. This effect will slightly affect the heating and cooling of the specimen, therefore the second profile is vital to the understanding of the temperature gradient across the specimen with fewer TC's covering the surface.

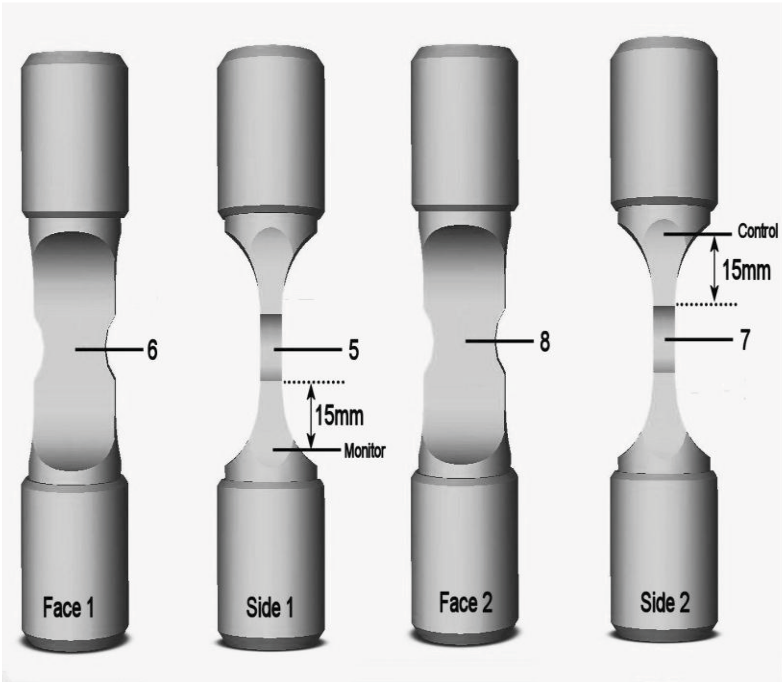

Figure 6: Stage 2 thermal profiling. 4 TC's are positioned around the gauge section of the specimen and control and monitor TC's at the adjacent shoulders.

Stage 3 thermal profiling is performed after removing the four TC's at the gauge section but retaining the control and monitor TC's (Figure 7). The temperature profile focuses only on matching the profile of the control and monitor TC's from stage 2. The furnace control and air cooling must remain unchanged. The only option is to move the furnace vertically, up or down, a few millimetres are usually sufficient.

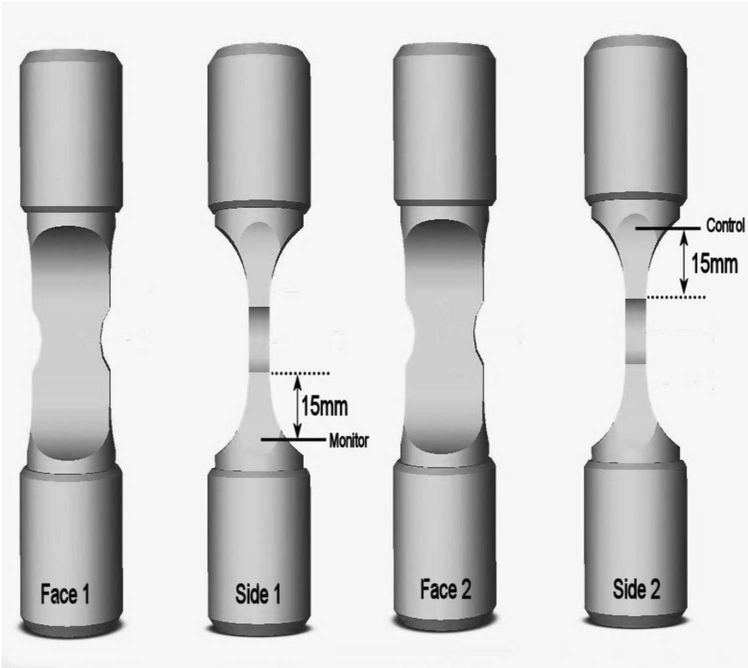

Figure 7: Stage 3 thermal profiling. Only the control and monitor thermocouples remain on the specimen shoulders

Validation and testing

Once stage 3 has been successfully profiled, a test specimen can replace the dummy profile specimen for final validation. The test specimen is placed in the same position in relation to the depth of thread in the columns, its orientation in relation to the furnace, i.e. flat faces perpendicular to the front of the testing frame, etc. New control and monitor TC's are spot welded to the shoulders and then the specimen and TC's are pre-oxidised in the furnace for a minimum of 6 hours at 400^{o}C. The subsequent thermal profile has now to match the last accepted thermal profile from stage 3. Once this is achieved the appropriate load can be applied to the test cycle. After ten cycles with the appropriate loads the thermal profile is again checked for deviation from stage 3. Only if the thermal cycle falls within the tolerances already achieved in stage 3, can the test run to failure. Appropriate limits are set in the software to monitor temperature deviation and suspend the test if they are exceeded.

The subsequent stress TMF test is representative of some of the extremes that the gas turbine feature in question encounters and is performed under largely out-of-phase conditions using a complex cycle. The first test specimen failed at the notched groove, which after fracture surface investigation, was verified as being a valid result. Following this another two machines were validated for performing this test method. Furthermore, on the satisfactory completion of the stress controlled TMF testing of the Udimet 720Li, the same stress controlled TMF test method was successfully performed on the alloy RR1000 with its own feature based geometry. The future goal is to have six machines running this test method.

Conclusions

Stress controlled TMF was successfully performed on two alloys with different feature based geometries. This test method has subsequently been repeated on other testing machines of the same type without any discrepancies in the results. The test results have validated the robustness and reliability of the test. The success of the stress controlled TMF test has encouraged Rolls-Royce to lead the development for a new Code of Practice for this test method.