HT-TMF Conference, Berlin, 22/23 Sept. 2005, International Journal of Fatigue.

Temperature gradients in TMF specimens

Measurement and influence on TMF life

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Abstract

Axial stress components caused by radial temperature gradients in TMF-specimens lead to local control deviations in temperature and mechanical strain. Measurements and simulations have been carried out in order to estimate the level of control deviation in anisothermal heated TMF specimens. Thermal cycle tests were carried out with a variety of specimen coil configurations which cause different radial temperature profiles. Temperature gradients were measured by means of instrumented specimens under different heating and cooling rates.

In order to calculate the resulting stresses, model parameter of a thermal-mechanical FE-analysis (e.g. coefficient of convection, emmisivity and heat transfer) were fitted on the basis of the measured temperature distribution.

TMF tests have been carried out on Ni90 specimens with two induction coil configurations and with two different heating and cooling rates. The experimental results were reported and discussed on the basis of the measured and simulated results.

Keywords: thermo mechanical fatigue, temperature distribution, control deviation

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1 Motivation

TMF cycles occurring in highly loaded components such as turbine blades are caused by inhomogeneous temperature distribution in the bulk of the component. One of the goals of TMF-testing is to create a data base for the life time prediction at critical spots of thermo-mechanical loaded components. This is achieved by referring to standardised tests with comparable temperature range and usually an “out of phase cycle” (OOP), which is the most damaging. Eventually a special design cycle is defined and tested. An important requirement for a reliable TMF lifetime statement is to reproduce the calculated temperature cycle homogeneously in the entire specimen gauge length volume.

However, inhomogeneous temperature distributions caused by physical boundary conditions, in particular during transient sections of the temperature trajectory, are unavoidable even in the case of an excellent optimized TMF test set up. Therefore it is necessary to estimate the level of additional stress components which are thermally induced and their effect on TMF-life.

2 Thermal cycle tests

2.1 Temperature Measurement

The influence of different triangular temperature cycles on the temperature distribution was investigated. The following cycle parameters have been selected:

- Heating and cooling rates: 5K/s, 10K/s and 20K/s
- Temperature range: 400-850°C.

All measurements were performed under authentic test conditions with flat specimens (Fig. 1) equipped with five coaxial thermocouples (1mm diameter) in mid cross section (Fig. 2).

During cycling the control loop feed back signal was provided by a ribbon shaped thermocouple which was bent around one narrow side of the specimen and pulled to the specimen surface by a weak spring force (Fig. 2). All temperature signals were acquired synchronously to allow the calculation of the temperature deviations versus cycle time.

Ribbon shaped thermo couples were manufactured by MTU. A laser welding apparatus was used to butt weld the two individual thermocouple S^+ and S^- wires (0.35mm diameter). Subsequently the wire was flattened by compression to 1.2mm…1.5mm in thickness over a length of approximately ±10mm symmetrically to the welding point.

2.2 Coil - Specimen Configurations

Different temperature gradients in the specimen were achieved by changing the induction coil design and its position with respect to the specimen. Two different designs of induction coils were developed and three different cases were investigated Fig. 3:

Configuration 1 is characterised by a cylindrical coil with its middle axis coinciding with the specimen centre axis. The flux lines run parallel to the specimen centre axis.

In configuration 2 and 3 an elliptical coil, with its middle axis perpendicular to the middle axis of the specimen, was utilized. This type of coil was specifically optimized for homogeneous heating of flat specimens with rounded corners. This coil design was tested with two different arrangements:

- 0° rotation (usual set up for TMF testing), where the flux lines are orientated parallel to the flat surfaces of the specimen (configuration 2)
- 90° rotation, where the flux lines are orientated perpendicularly to the flat surfaces of the specimen (configuration 3)

All configurations were tested with heating/cooling transients of 5K/s, 10K/s and 20K/s. The temperature measurement of all thermocouples was performed synchronously during heating and cooling. Cooling ramps were controlled by cooling air nozzles optimized for homogeneous forced convection all over the specimen surface.

2.3 Results of thermal cycle tests

Fig. 4 shows curves of temperature deviation vs. time measured with a triangular cycle with 10K/s transient. Similar diagrams were generated for every setup/transient combination under investigation. The characteristics of the observed radial temperature gradients are:

- Configuration 1: The cylindrical coil causes radial gradients with maximum temperature at the centre axis of the specimen. The rounded corners were distinctively cooler than the specimen volume. The flux lines are concentrated at the centre axis.
- Configuration 2: The rectangular coil with 0° rotation caused the lowest gradients.
- Configuration 3: The rectangular coil with 90° rotation caused the highest radial gradients with the maximum temperature at the rounded corners.
- To all configurations: The radial temperature gradients increased with higher heating/cooling rates.

The temperature gradients are listed in Table 1. The temperature deviation “Center TC to TC in 3mm distance” which is the inner gradient, was calculated by subtracting the signal of T5 (centre TC) from the average signals of the eccentric coaxial thermocouples T1 and T3. This approach allows to compensate the effect of slight misalignment errors between coil or cooling air nozzles and specimen. All gradients are read at mean temperature during cooling and heating.

3 Thermal Mechanical FE-Analysis

3.1 Model description

Finite element analysis of the induction heated TMF specimen geometry was carried out with the following physical boundary conditions:

- Heat generation within the first 1 mm underneath the specimen surface because of the RF penetration characteristic. Heat flux as a function of pre-recorded heating control signal.
- Natural and forced convection at specimen surface as a function of the pre recorded cooling control signal.

- Radiation at specimen surface, ε=0.75.
- Heat conduction to the grips α=2000W/(m^2*K)
- Non linear longitudinal flux line density of the coil.
- Non linear transversal flux line density in the case of the 90° rotated specimen (conf. 3)

The parameters of the FE model (e.g. emmisivity, coefficient of convection, gap conduction between specimen and grips) were optimized with respect to measured temperature values of a 20K/s cycle. The polynomial coefficients of the function which describes the dependence of the heat flux density on the z-coordinate were fitted in order to meet the temperature gradient in the specimen volume of configuration 3. No z-axis dependence was implemented in the "homogeneous" model.

3.2 Simulation Results

The FE analysis of the low-gradient setup (configuration 2) indicates lower temperature gradient during heating and higher gradient during cooling. The highest gradient during cooling was caused by the forced convection at the specimen surface due to strong cooling air flow (Fig. 5, Fig. 6).

A summary of the FE results for the homogeneous setup (configuration 2) in the range of 700°C during heating and cooling is listed below:

- Temperature gradient during heating: ±3K.
- Resulting axial stress gradient during heating: -4...+9MPa.
- Temperature gradient during cooling: ±9K
- Resulting axial stress gradient during cooling: -25...+36MPa.
- Maximum tension stress during cooling (36MPa) was found at the surface of the rounded corners (lowest temperature).

A second, dynamic FE analysis of the high-gradient setup during heating up (configuration 3) has been carried out and evaluated in the range of 700°C (Fig. 7, Fig. 8). The results indicate a high stress gradient. The simulation results are summed up in the following:

- Temperature gradient during heating: ±22K
- Resulting axial stress gradient during heating: -74...+53MPa

- Maximum compression stress (-74MPa) at surface of rounded corners (highest temperature)

The characteristic and the level of the simulated temperature gradients in the specimen volume correspond essentially to the measured results of the instrumented specimen. However the measured gradients from specimen centre to surface exceed the simulated gradients.

These deviations during heating and cooling can be explained by the measurement error of the ribbon shaped thermo couple. Physical boundary conditions like non-ideal heat transfer between specimen surface and TC, heat conductance from welding point to cooler sections of the TC wire or higher convection rate due to local surface enlargement (cooling fin effect) lead to a negative measurement error. The error level has been estimated on the basis of thermal strain data to be in the range of -10K at Tmax, -20K at Tmin.

4 TMF Tests

4.1 Thermo-mechanical fatigue tests conditions

For investigating the influence of the thermally induced axial stress components on the thermo-mechanical fatigue lifetime, TMF tests were performed with Nimonic90, a polycrystalline nickel base super alloy. In the thermo-mechanical fatigue tests the total strain was measured using a high temperature extensometer with a 12 mm gauge length attached with ceramic rods to the specimen. The thermal strain, as a function of the temperature, was determined prior to the actual test under load-free conditions. To achieve a proper test control with the mechanical strain, the required strain vs. time function was added to the thermal strain vs. time signal to get the total strain vs. time signal, which was then used as the control signal during testing. The specimen temperature was measured with a ribbon shaped thermocouple attached to the middle of the gauge length.

All tests were performed with an OOP cycle (phase shift of 180°) and a strain ratio of $R_\varepsilon = -1$. The minimum temperature for all tests performed was 400°C and the maximum temperature was 850°C. Two different heating and cooling rates and two different coil arrangements were applied in order to test the most homogeneous and the most inhomogeneous set up. The test parameters are summarized in the test matrix in Table 2. Cooling was performed by four air nozzles directed to the centre area of the specimen surface. The cooling air flow was proportionally controlled. The mechanical strain range was in all cases 0.8%.

4.2 Test results

The parameters and results of the different tests are summarized in Table 2, where T_{min} is the lowest temperature, T_{max} is the highest temperature, $\Delta\varepsilon_{mech}$ is the mechanical strain range applied, $\Delta\sigma$ is the stress range during the test and N_f the number of cycles to failure. The failure criterion was either a 30 % drop of the stress amplitude or the fracture of the specimen.

The results for the low gradient arrangement show no distinct influence of the heating/cooling rate (5K/s vs. 20K/s) on the thermo-mechanical fatigue life of the specimens. The specimens tested with a high gradient arrangement and high heating and cooling rate (20K/s), show a tendency to longer thermo-mechanical fatigue life, in comparison with the other tests. However this tendency concurs with the scatter band for all tests.

5 Summary and conclusions

Configuration 2 (MTU coil 0° rotated)

- Configuration 2 is optimised for low temperature gradients. Thermally induced, axial stress components during heating are negligible.
- Calculated thermally induced, axial stress components during cooling with 20K/s are in the range of 30 MPa at 700°C and even higher at lower temperature.

Configuration 3 (MTU coil 90° rotated)

- Configuration 3 was selected for investigating the influence of thermal gradients on TMF-life. The simulation of the heating ramp indicates thermally induced, superposed axial stress components of -70…-80MPa due to thermal gradients in the range of ±22K.

TMF tests with configurations 2 and 3

- TMF tests with Ni90 specimens showed no distinct dependence of cycle number to failure on different temperature gradients or heating/cooling rates. The high gradient experiments turn out to show a slightly higher number of cycles to failure. The following facts may allow to explain this effect observed on configuration 3 experiments:
    - Temperature was measured and controlled at the location of T_{max} (rounded edges). The mean gauge length temperature was distinctively lower since a big portion of the gauge length volume reached 40…50K lower temperature levels than the rounded edges.
    - During the heating ramp the damaging tension stress is reduced for 70…80MPa in the vicinity of the "hot" rounded corners of the specimen due to the superposed thermally induced compression stress.

Based on the available results no general statement about the influence of superposed, thermally induced stress components on the experimentally measured TMF-life time is possible. Only one combination of cycle shape and material has been tested where no significant influence is observable. The damaging potential of the loading cycle at the hot-spot location was obviously not increased in comparison with the homogeneous setup (configuration 2). Due to positive mean stress shift caused by out-of-phase-TMF loading the superposed compression stress reduces the damaging stress during heating.

The gradients in configuration 3 may have the potential to reduce the experimentally measured TMF life in the case of in-phase experiments with negative mean stress shift. In such a case, the compression stress would be increased at the hot-spot locations.

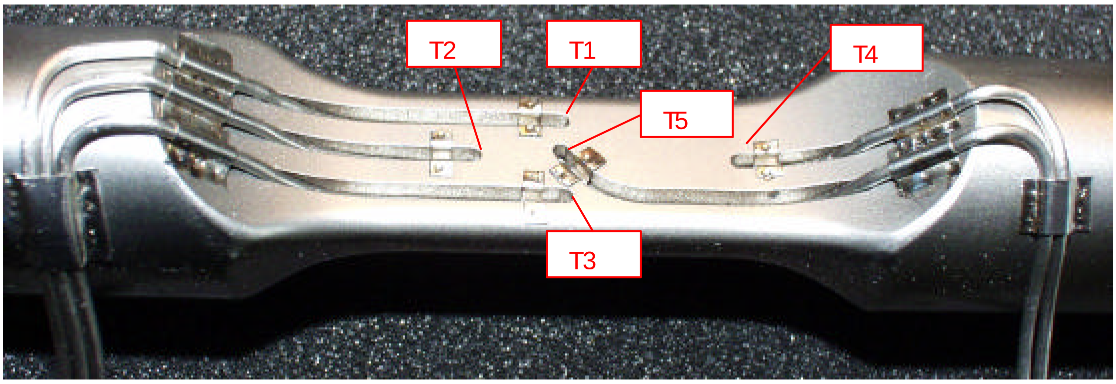

Fig. 1 Instrumented TMF specimen with coaxial thermocouples fixed in eroded slots prior to soldering.

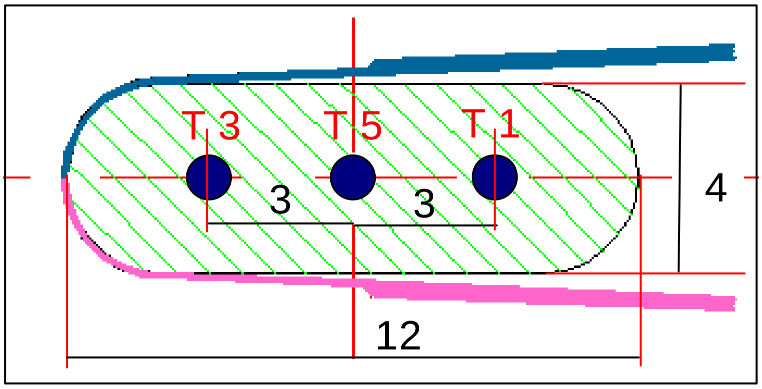

Fig. 2 Ribbon shaped thermo couple aligned to the narrow side of an instrumented TMF-specimen (4mm x 12mm). Centre coaxial TC (T5) and eccentric coaxial TCs (T3, T1) in the gauge length cross section.

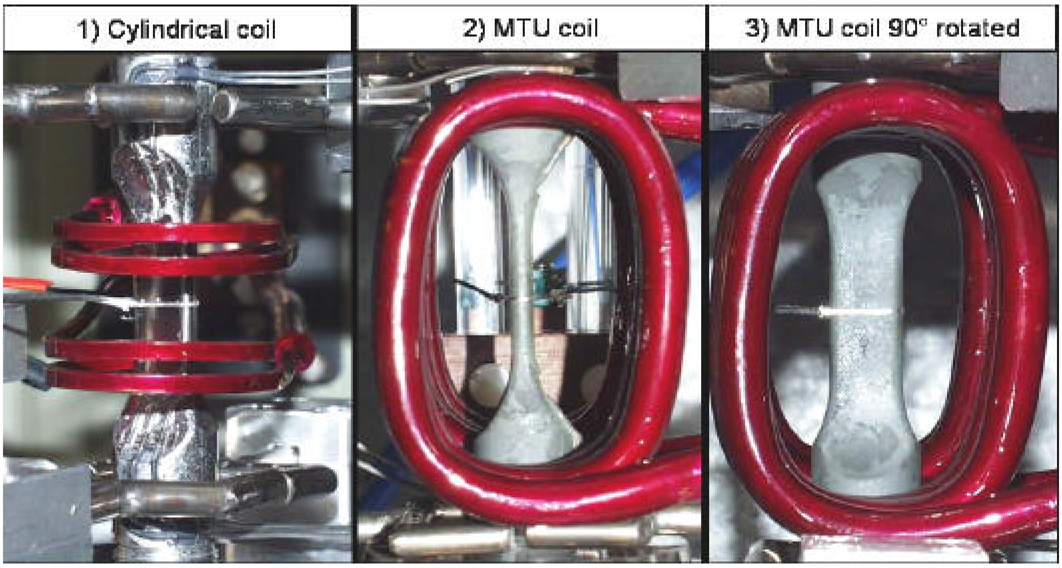

Fig. 3 Three different coil-specimen configurations: Configuration 1: Cylindrical coil, 40mm diameter and 30mm height. Configuration 2: MTU-standard coil. Configuration 3: MTU-standard coil with specimen 90° rotated.

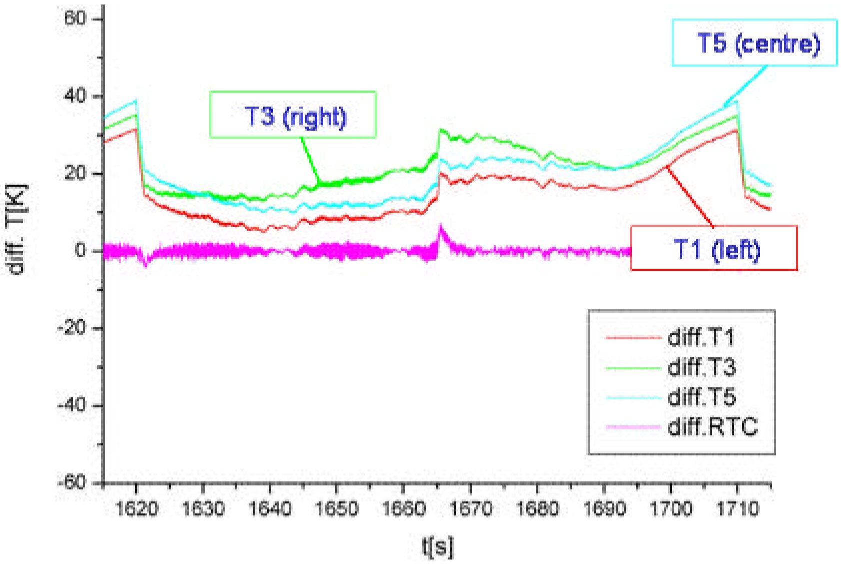

Fig. 4 Temperature deviation of ribbon shaped TC, TC1, TC3 and TC5 to temperature command variable. Configuration 2 (elliptical coil 0° rotated), 10K/s heating and cooling rate, Tmax=850°C, Tmin=400°C. T3 ≠ T1 due to misalignment between coil and specimen.

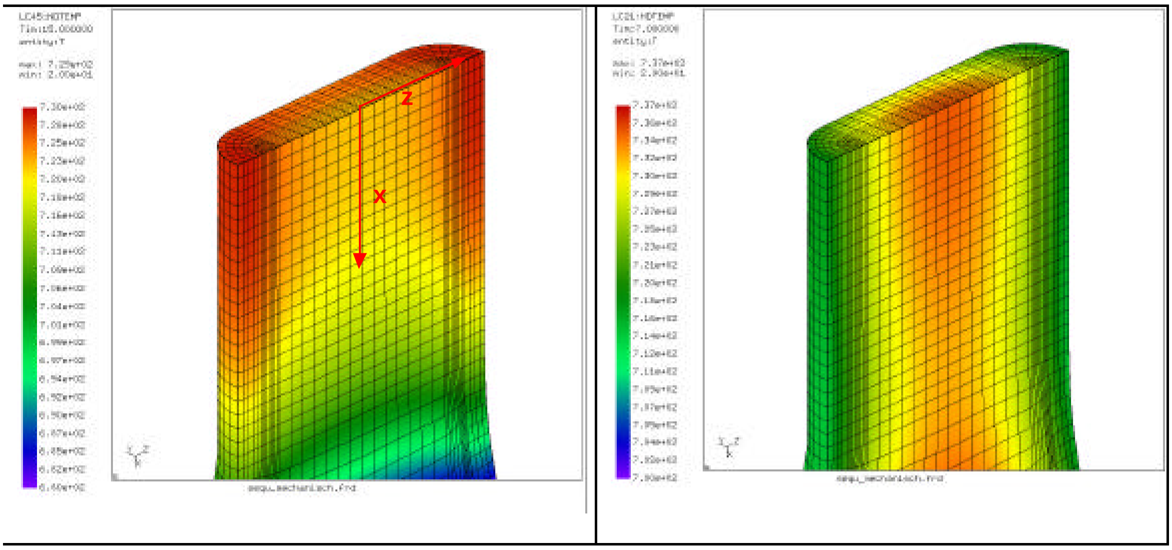

Fig. 5 Simulated temperature distribution during heating (left) and cooling (right), with 20K/s heating and cooling rate, of an inductively heated TMF specimen under “homogeneous” (Configuration 2) conditions.

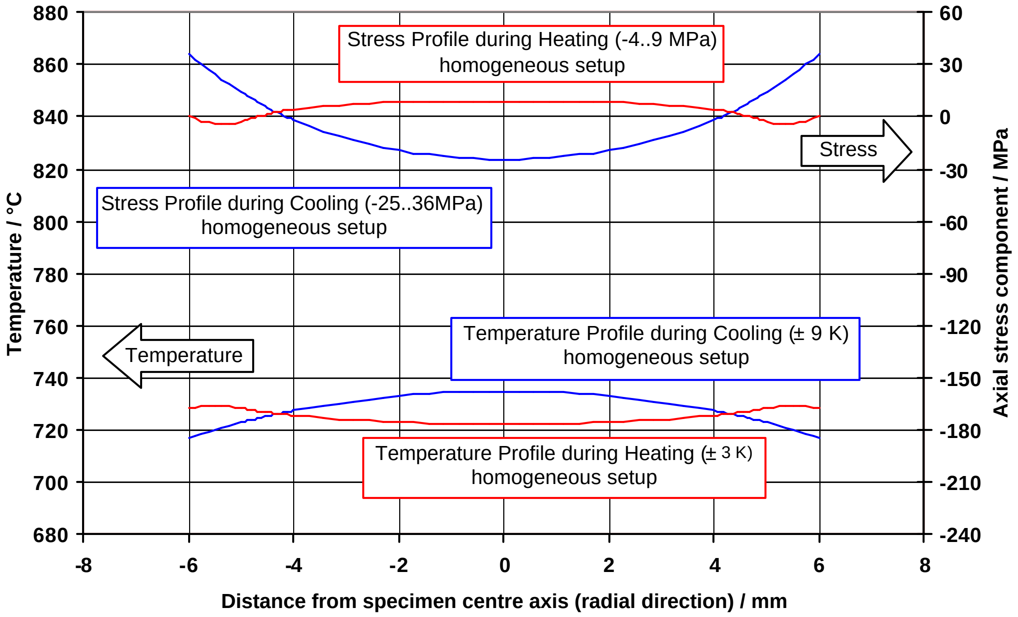

Fig. 6 Diagram of simulated radial temperature gradients with 20K/s heating and cooling rate and the resulting, thermally induced axial stress components corresponding to configuration 2 (homogeneous) in Fig. 5

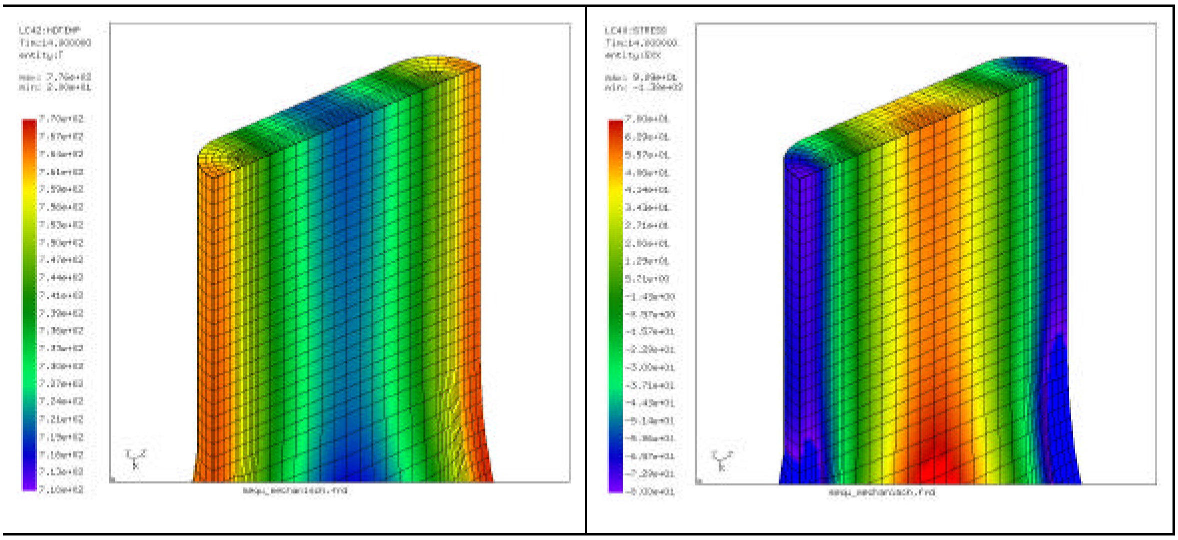

Fig. 7 Simulated temperature distribution (left) and resulting axial stress component (right) during heating of an inductively heated TMF specimen under “inhomogeneous” (Configuration 3) conditions.

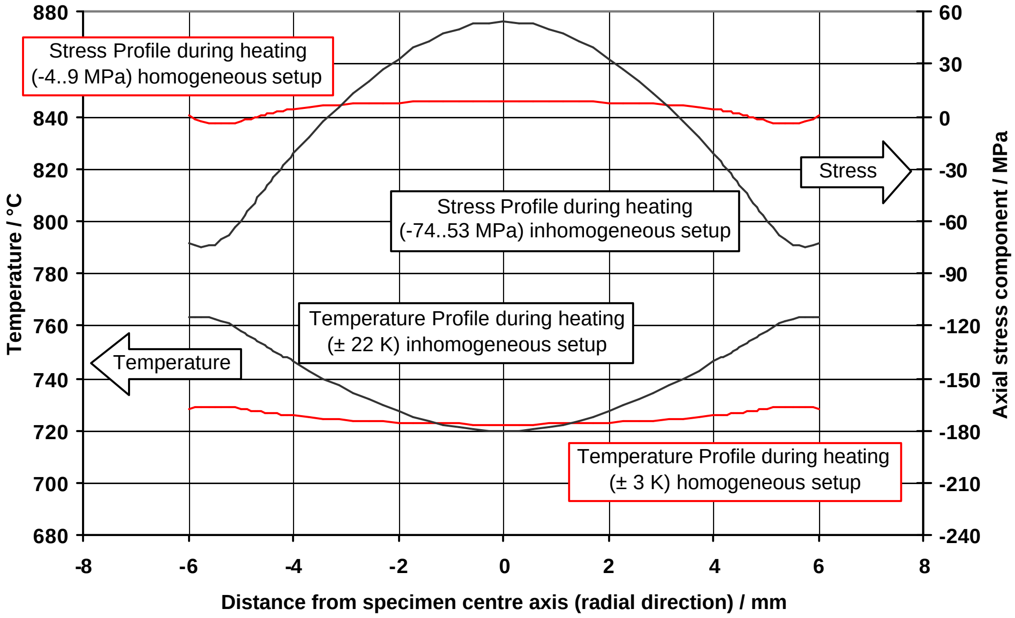

Fig. 8 Diagram of simulated radial temperature gradients and the resulting, thermally induced axial stress components during heating corresponding to configuration 3 (inhomogeneous) in Fig. 7

Gradients during heating and cooling at mean temperature				
Triangular cycle 400°C..850°C, instrumented specimen				
	(all values in K)	Conf. 1	Conf. 2	Conf. 3
Heating ramp 5K/s	Center TC to TC in 3mm distance	-5	3	20
	Center TC to surface TC	-40	-13	40
Heating ramp 10K/s	Center TC to TC in 3mm distance	-10	3	20
	Center TC to surface TC	-50	-15	45
Heating ramp 20K/s	Center TC to TC in 3mm distance	-15	-3	30
	Center TC to surface TC	-50	-18	60
Cooling ramp 5K/s	Center TC to TC in 3mm distance	-10	-1	7
	Center TC to surface TC	-50	-15	13
Cooling ramp 10K/s	Center TC to TC in 3mm distance	-15	-3	5
	Center TC to surface TC	-60	-20	10
Cooling ramp 20K/s	Center TC to TC in 3mm distance	-15	-10	0
	Center TC to surface TC	-70	-45	-20

Table 1:Summary of measured radial temperature gradients of 3 specimen coil configurations with 3 heating/cooling transients.

Heating/ cooling rate [K/s]	**Spec. id.**	**Coil setup**	**T_{min} [°C]**	**T_{max} [°C]**	**$\Delta\varepsilon_{mech}$ [%]**	**$\Delta\sigma$ [MPa]**	**N_f**
5	Ni90TMH01	Low gradient	400	850	0.8	1029	1113
	Ni90TMH02	Low gradient				976	1332
	Ni90TMH08	Low gradient				1052	1084
20	Ni90TMH03	Low gradient	400	850	0.8	1062	1293
	Ni90TMH04	Low gradient				1015	1595
	Ni90TMH09	Low gradient				1080	1084
20	Ni90TMH05	High gradient	400	850	0.8	1083	1678
	Ni90TMH06	High gradient				1098	1848
	Ni90TMH07	High gradient				1136	1609

Table 2:Parameters and results for all the Nimonic 90 specimens tested. Coil arrangement “Low gradient” represents configuration 2. Coil arrangement “High gradient” is identical to configuration 3.