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EU-project SMILE / Validation of the WPS Effect with a Component like Cylindrical Specimen

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Abstract

The Reactor Pressure Vessel (RPV) is an essential component, which is liable to limit the lifetime duration of PWR plants. The assessment of defects in RPV subjected to pressurized thermal shock (PTS) transients made at an European level generally does not necessarily consider the beneficial effect of the load history (Warm Pre-stress, WPS). The SMILE project - Structural Margin Improvements in aged embrittled RPV with Load history Effects - aims to give sufficient elements to demonstrate, to model and to validate the beneficial WPS effect. The project includes significant experimental work on WPS type experiments with C(T) specimens and a PTS type transient experiment on a large component.

This paper deals with the results of the PTS type transient experiment on a component-like, specimen subjected to WPS- loading, the so called Validation Test, carried out within the framework of work package WP4. The test specimen consists of a cylindrical thick walled specimen with a thickness of 40 mm and an outer diameter of 160 mm, provided with an internal fully circumferential crack with a depth of about 15 mm. The specified load path type is Load-Cool-Unload-Fracture (LCUF). No crack initiation occurred during cooling (thermal shock loading) although the loading path crossed the fracture toughness curve in the transition region. The benefit of the WPS-effect by final re-loading up to fracture in the lower shelf region, was shown clearly. The corresponding fracture load during reloading in the lower shelf region was significantly higher than the crack initiation values of the original material in the lower shelf region. Some results of accompanying calculations will be shown.

NOMENCLATURE

K - stress intensity factor (MPa·m$^{1/2}$)
SIF- stress intensity factor (MPa·m$^{1/2}$)
T - temperature (°C)
E,E' – Young's Modulus
t - time (s)
α- circumferential position (°)
a – crack depth (mm)
p_i – internal pressure (MPa)

1 INTRODUCTION

The integrity of the reactor pressure vessel (RPV) of nuclear power plants (NPP) is essential to its safe operation. A hypothetical rupture of the vessel has the potential to cause a massive loss of coolant, overheating of the reactor core, and a subsequent major release of radioactivity to the environment. As part of the assurance of structural integrity, the RPV structural integrity analyses on the basis of fracture mechanics considers the behavior of defects under normal and abnormal loading conditions. It assesses safety margins and component lifetimes as material degrades due to irradiation and (or) thermal ageing. These integrity analyses compare load and resistance terms to demonstrate that the crack driving force does not exceed the vessel material fracture toughness during the entire transient, (loading and unloading parts of the transient). Generally fracture toughness data are derived from tests performed on standard (deeply-notched) specimens to ensure data representing high hydrostatic stresses near the crack tip (high constraint) and plane strain conditions. This will provide a lower bound material property independent of specimen size. In some countries (such as France), the structural integrity assessment of a RPV subjected to PTS transients doesn't take into account the potential beneficial effect of the load history ('warm pre-stress WPS') on the vessel resistance regarding the risk of brittle failure. This has some major consequences:

- A potentially over-conservative assessment of the margins associated with the loading to which the component (RPV) is subjected,
- A potential economic penalty due to under-estimation of the component safe lifetime.

A 3-years European Research & Development project (SMILE) started in January 2002 as part of the Fifth Framework Programme of the European Atomic Energy Community (EURATOM).

At MPA Stuttgart experimental WPS-simulations with C(T)-specimen [1-3] were carried out to prove the validity of the WPS-principle. These investigations [3] have shown clearly: "no fracture at constant and decreasing load or dropping temperature". Fracture was only initiated if the load increased at lower reloading temperatures. The level of the warm pre-stress determined mainly the reachable reloading level at fracture. The progress of the transient, especially the degree of unloading following the maximum and the specimen size, was identified as additional influencing factor.

2 SMILE PROJECT

SMILE 'Structural Margin Improvements in aged-embrittled RPV with Load history Effects' is one of a 'cluster' projects in the area of Plant Life Management. It aims to demonstrate on small and large scaled specimens, to model and to validate the beneficial effect of the warm pre-stress in a RPV structural integrity assessment. Finally, this project shall harmonize the different approaches as the general basis for European codes and standards regarding the inclusion of the WPS effect in a RPV assessment. The SMILE project is organized in 6 work packages, Table 1.

2.1 Purpose of project and expected results

The aim of this project is to show and better understand the effect of the warm pre-stress (WPS) in a RPV structural integrity assessment, and to define and establish some recommendations and guidelines for a pre-codification in main European codes and standards. The beneficial effect of the load history ('warm pre-stress') on the vessel resistance regarding the risk of brittle failure can be summarized as follows:

Brittle failure is excluded during the unloading of the vessel (decrease of the stress intensity factor K_J versus temperature T, even if the loading path K_J – T intersects the material fracture toughness curve). In case of a final reloading of the vessel at lower temperature, the brittle failure would be obtained with beneficial and substantial margins compared to material fracture toughness obtained on a 'virgin' material. Elements necessary to propose a methodology to take into account WPS in a RPV assessment will be investigated. This is to be carried out by experimental work on conventional fracture mechanics specimens, such as C(T) specimens, and a 'large-scale' component in terms of a cracked cylinder submitted to a PTS type transient leading to a better understanding of metallurgical and mechanical phenomena, and through the development (or improvement) of analytical and numerical models. The results obtained during this project will permit a more precise prediction of a possible brittle failure in a RPV submitted to a severe overcooling transient.

2.2 Participants

The consortium consists of 11 partners. The expertise of the members is both interdisciplinary and complementary in many fields. It includes three utilities (EDF, BE and E.ON), a manufacturer (Framatome-ANP & Framatome-ANP GmbH, the largest European RPV manufacturer), four research organizations (CEA, SERCO, IWM Freiburg as subcontractor of E.ON and MPA Stuttgart), one European research laboratory (JRC Petten, Institute of Energy), one safety authority (BCCN) and one US National Laboratory (ORNL with the sponsor of the US NRC). Except of the French Safety Authority, all the participants – including ORNL - are members of the NESC network [4].

3 WP4 VALIDATION TEST – TEST PROGRAM

A major feature of the SMILE-project is to demonstrate the warm-pre-stress-effect (WPS) under thermal shock conditions. Thus, a model vessel (hereafter referred to as test specimen) containing a circumferential crack was tested under combined thermal and mechanical loading. This validation test was specifically designed to produce a pronounced preloading in the upper shelf region of fracture toughness without crack initiation and to show the benefit of WPS-effect by final loading up to fracture in the lower shelf region.

An important boundary condition was determined by the available test technique: cooling can only be carried out by means of water at ambient temperature (room temperature RT). This made it necessary to choose a material with a lower shelf fracture toughness in the room temperature (RT) range.

WP	Tasks	WP Leader
WP1	**Co-ordination and Management**	**EDF**
WP2	**Calibration tests** **WP2.1** Characterization of the degraded material **WP2.2** Confirmation of the WPS effect on degraded material (WPS3) **WP2.3** Calibration of WPS models on undegraded material (18MND5) **WP2.4** Load history effect on ductile tearing	**SERCO**
WP3	**Assessment of models** **WP3.1** Selection of models **WP3.2** Validation of models against existing data (WPS3 & 18MND5)	**CEA**
WP4	**Validation test** **WP4.1** Test specification and design of test **WP4.2** Validation test **WP4.3** Fractography **WP4.4** INTERPRETATION OF VALIDATION TEST	**MPA**
WP5	**Cases studies** **WP5.1** Development of cases studies specifications **WP5.2** Application to a RPV sub clad flaw with an actual PTS transient **WP5.3** Application to a RPV through clad surface crack with an actual PTS transient	**FRAMATOME-ANP GmbH**
WP6	**Programme evaluation, synthesis and recommendations** **WP6.1** Guidelines for Codes & Standards **WP6.2** Conclusions and recommendations	**EDF**

Table 1: Description of SMILE work-packages

3.1 Material investigation

A model material, 17 MoV 8 4 mod., denominated WPS3, was available for which the mechanical properties had been changed by special heat treatment. These properties were tailored to simulate the properties of a reactor pressure vessel material after irradiation, with respect to strength, toughness and transition behavior. This meets the requirements of the planned transient curve and has the advantage that the material is very well characterized [1,3].

3.2 Geometry of specimen

The specimen consists of a cylindrical thick walled specimen with a thickness of 40 mm and an outer diameter of 160 mm. It has an internal fully extended circumferential crack with a depth between 14 mm and 15 mm. An initial crack depth of 12 mm was spark-eroded and further 2-3 mm were generated by pre fatigue-cracking.

3.3 Load path

The specified load path type is Load-Cool-Unload-Fracture (LCUF). The test specification was supported by extensive pre-test-calculations [5] to ensure that the objectives were met. The test program consisted of

- one „dummy test" to check the thermal transient and to define the thermo-physical parameters and
- the validation test, the main features of which are:

1. Pre-loading in the upper shelf region of fracture toughness.
2. Thermal shock according to the evaluated thermal transient.
3. Fracture by subsequent mechanical loading at RT.

4 TEST LOOP PROCEDURE

To realize the thermal transient in the cylinder, the cooling water feeding is performed with a water-spraying device, Fig.1. The operating mode of the cooling circuit - see also Fig. 2 - is:

1. Heating of the air-filled test specimen by means of heating mats
2. When the test specimen has reached the starting temperature of 300°C the pressure control valve is adjusted at p_i = 5 MPa.
3. After this the high-pressure pump (plunger pump) is started.
   First the whole water quantity (200 l/min) is delivered over the by-pass channel around the test specimen. The reason for this measure is that the control valve needs some time to reach a constant pressure. The advantage is to obtain immediately the full constant pressure and the full delivery volume at the beginning of the cooling water feeding.

4. When achieving a constant pressure in the bypass-channel the bypass-mode will be switched into the test mode. For this the 3/2-direction valve, see Fig. 2, will be opened and with a time delay of 50 ms as well the 2/2-direction control valve and the cooling process starts.

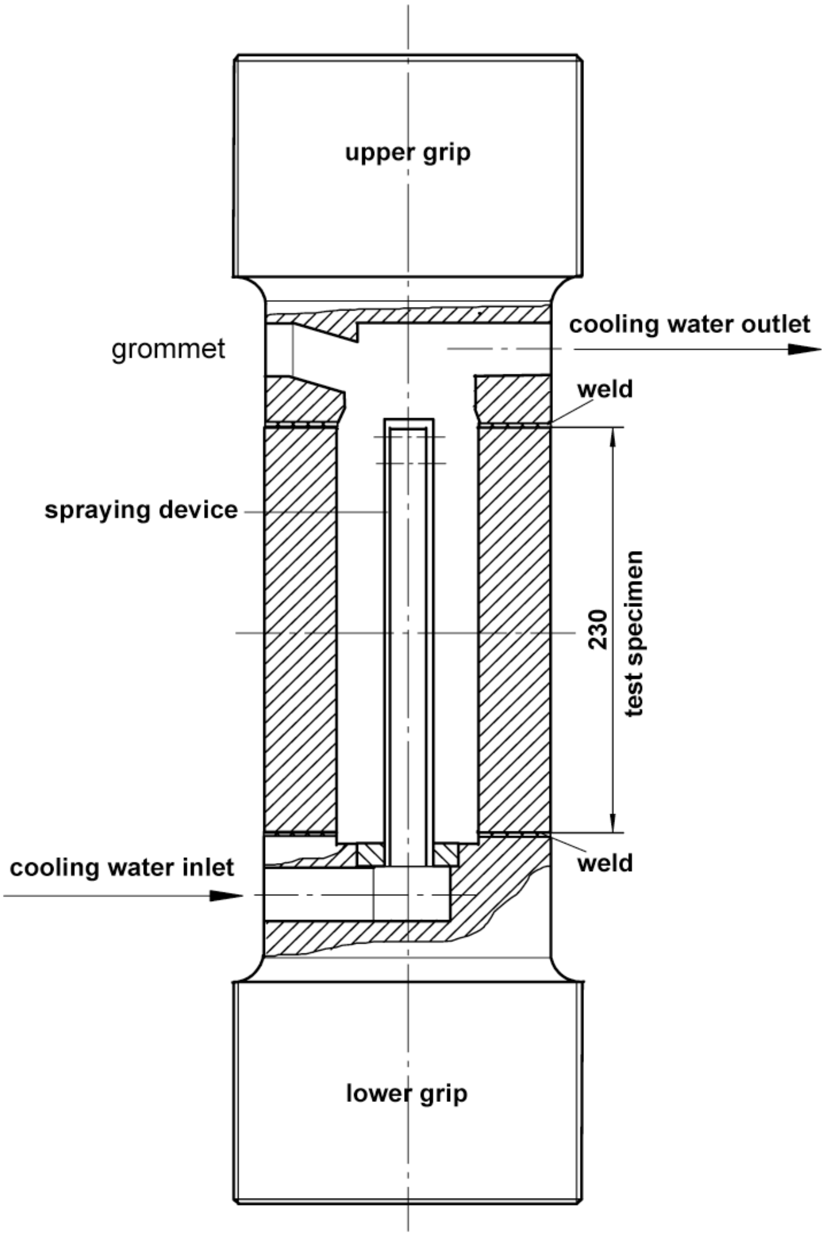


Fig.1: Principal drawing of the dummy and validation test specimen

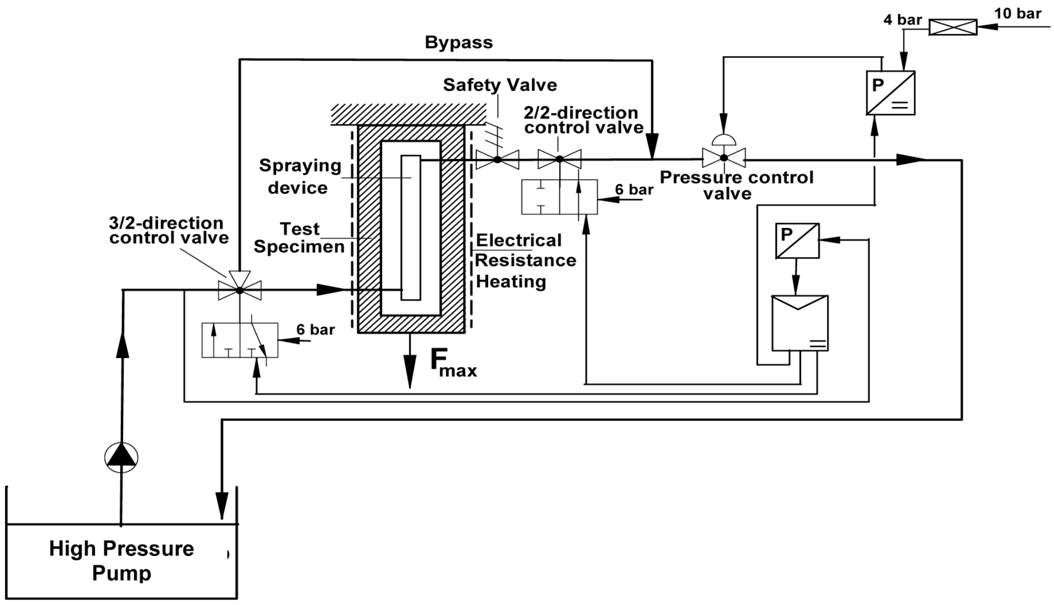


Fig. 2: Test loop for pressurized thermal shock experiments

5 INSTRUMENTATION OF TEST SPECIMEN

The situation just before the test is shown in Fig. 3. The geometry of the specimen and the key features of the instrumentation plan, consisting of clip gauges (G) for displacement measuring, strain gauges (DL = longitudinal, DU = circumferential) and thermo-couples (T = temperature of material, TF = temperature of fluid) are given in Fig. 4.

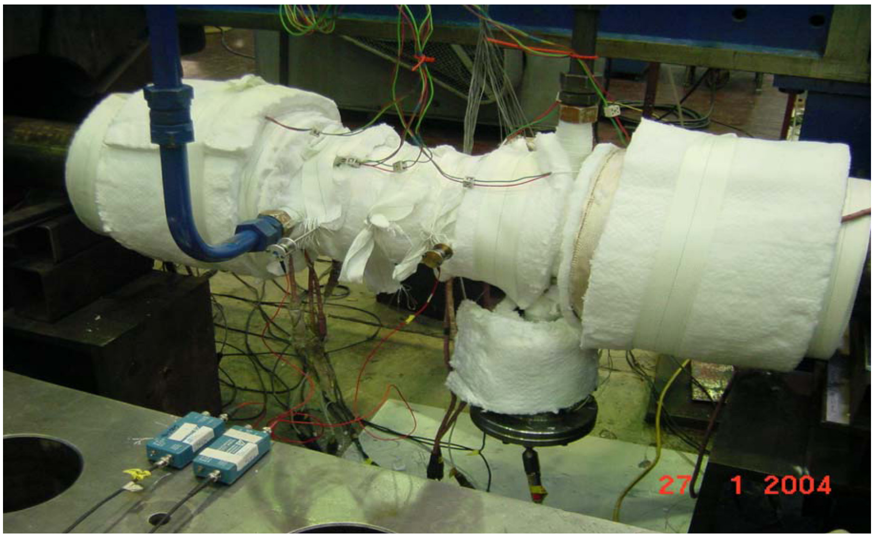
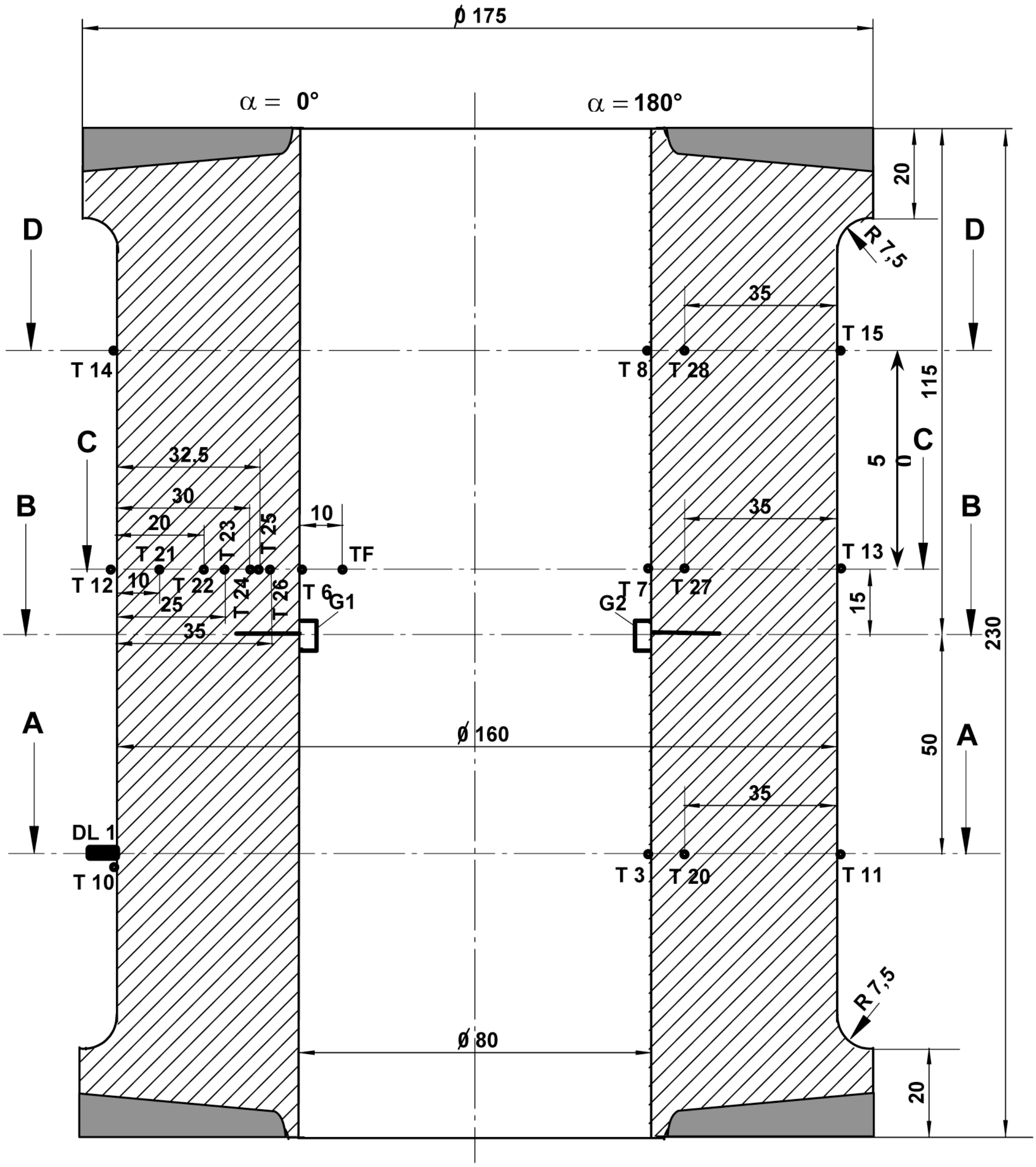


Fig.3: Specimen with instrumentation and insulation before test



G = clip gauge
T = thermocouple

Test Specimen (SMILE)

Plan of Instrumentation -longitudinal view-

Fig. 4: Cross-sections, position of clip gauges (G) for displacement measuring, strain gauges (DL = longitudinal, DU circumferential) and thermocouples (T)

6 SPECIFICATION OF LOAD PATH

The goal for pre-loading was defined in reaching a load level of about 10% under the lower line of the K_{IJ} – scatter band in the upper shelf region, where $K^2_{IJ} = E'J_i$. This value amounts to 75 MPa·m$^{1/2}$. Since this value cannot be reached by thermal shock loading only, an initial tensile load is applied. Fig. 5 shows the non-linear design-calculations of MPA by means of the Finite Element Code ABAQUS. 50%- and 5%- Master Curves, which have been corrected to the actual component crack length, are shown as well in Fig. 5. The influence of the total crack lengths on the Master Curves is rather small, so that the presented 50% Fract. and 5 % Fract. Master Curves (crack length: 346 mm, crack depth: 15 mm) are representative for all the depth values considered. Consequences for test design are

- Crack depth 4 mm: High risk of initiation during warm pre-stress
- Crack depth 12 mm: Low risk of initiation during warm pre-stress
- Crack depths 15 mm: Nearly no risk of initiation during warm pre-stress

The design calculations show that for crack depths greater than 12 mm the intersection-point with the Master Curves lies in the decreasing part of the loapaths, where there is no risk of failure due to the warm-pre-stress-effect. Fig. 6 shows the chosen load path.

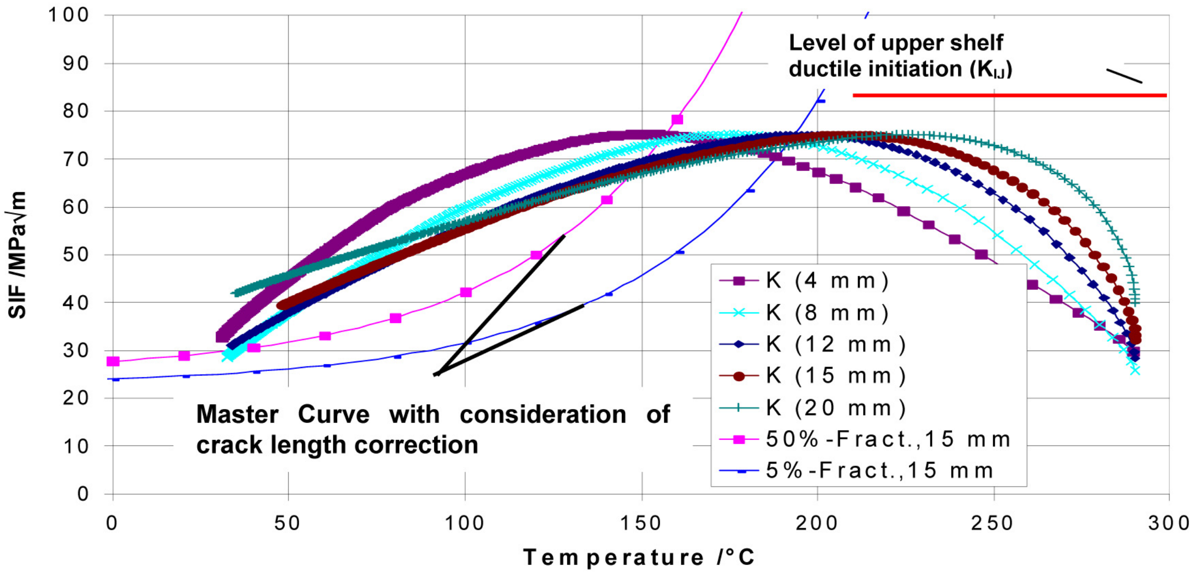


Fig. 5: Calculated load paths for crack depths 4, 8, 12, 15 and 20 mm of the Test Specimen

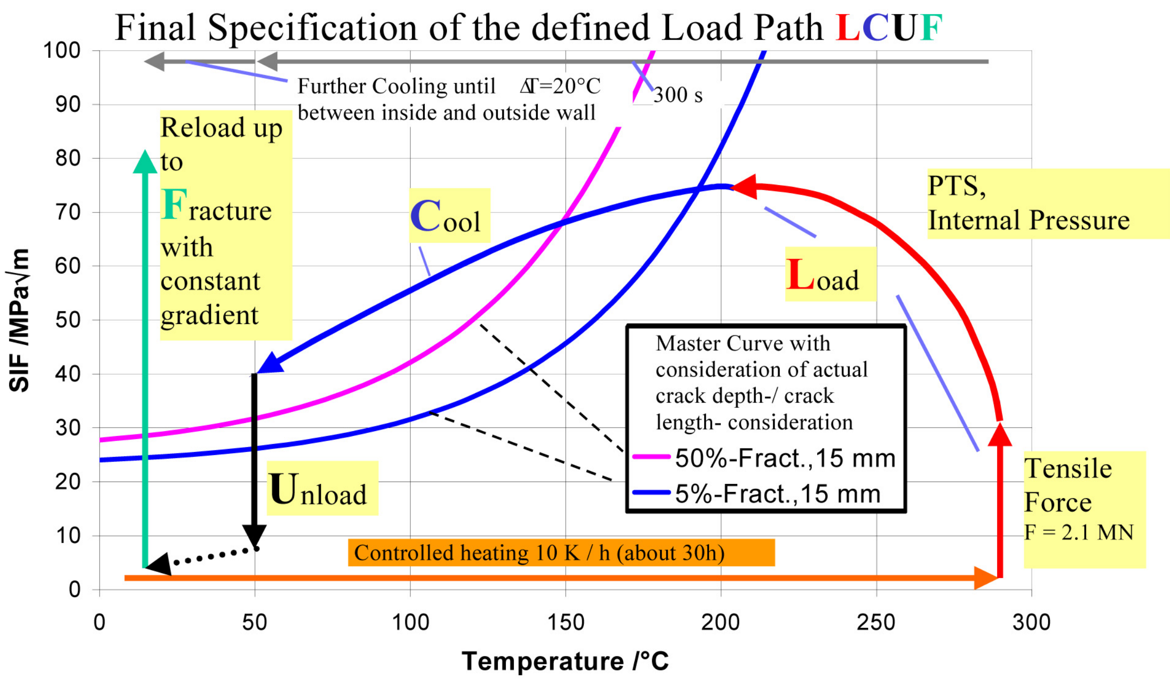


Fig. 6: Chosen load path

Based on these results, the validation test was performed with a nominal crack depth of 15 mm and a constant tensile load of 2.1 MN during the whole transient. The starting temperature was T = 290 °C. Reloading up to fracture was carried out at a loading rate of 2 MN/minute.

7 FATIGUE PRE-CRACKING

The initial crack was induced by electrical discharge machining (EDM) and then further extended by fatigue with internal pressure, Fig. 7. This produced slightly non-symmetric crack-growth and was stopped at an average crack depth of 14.3 mm based on online ultrasonic measurements. Post-test investigations of the crack surface yielded an average crack depth of 14.9 mm.

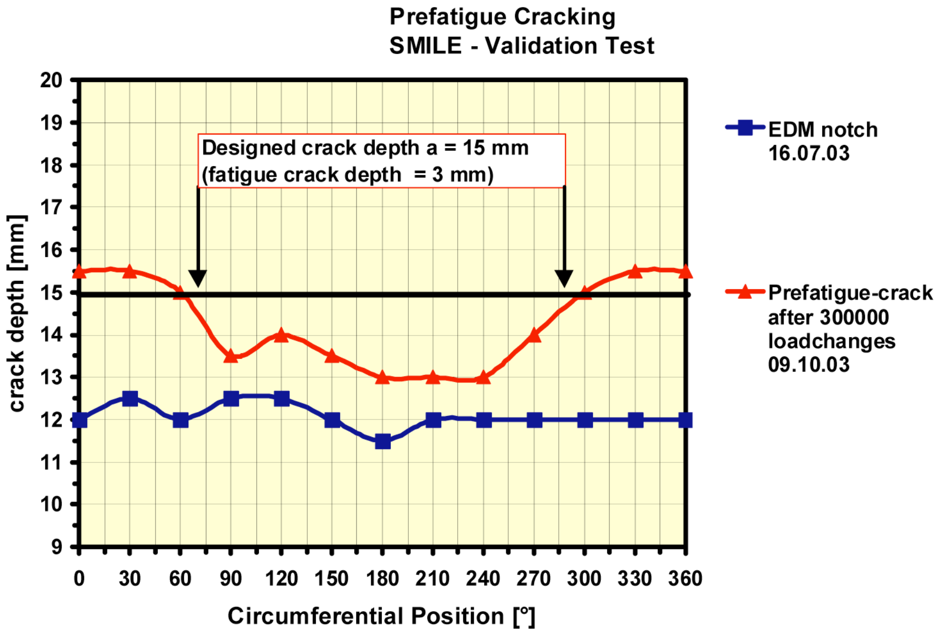


Fig. 7: Depth of the circumferential crack in the validation test specimen

8 TEST RESULTS

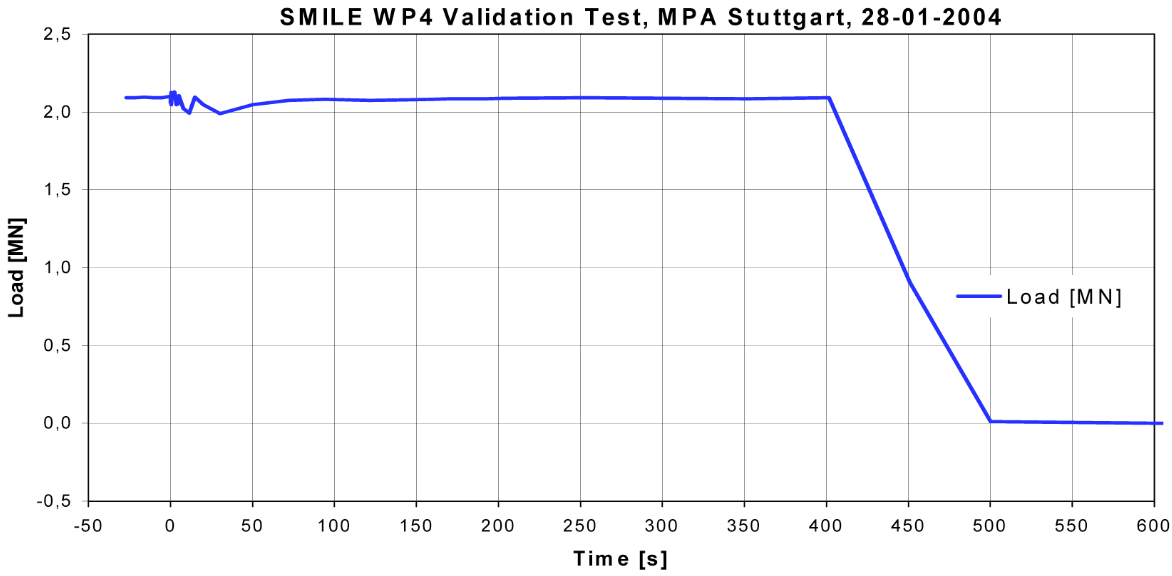
8.1 Thermal shock and unloading

As mentioned above the specimen was loaded by a combined tensile load and thermal shock. The tensile load applied by the testing-machine is regulated manually. Immediately after thermal shock at t ~ 0 s the tensile load was held at a value between 2.0 MN and 2.1 MN until 400s after starting PTS (Fig. 8). On-line calculations of K_I versus time on the basis of measured temperatures showed that the real load path was close to that specified, Fig. 9.

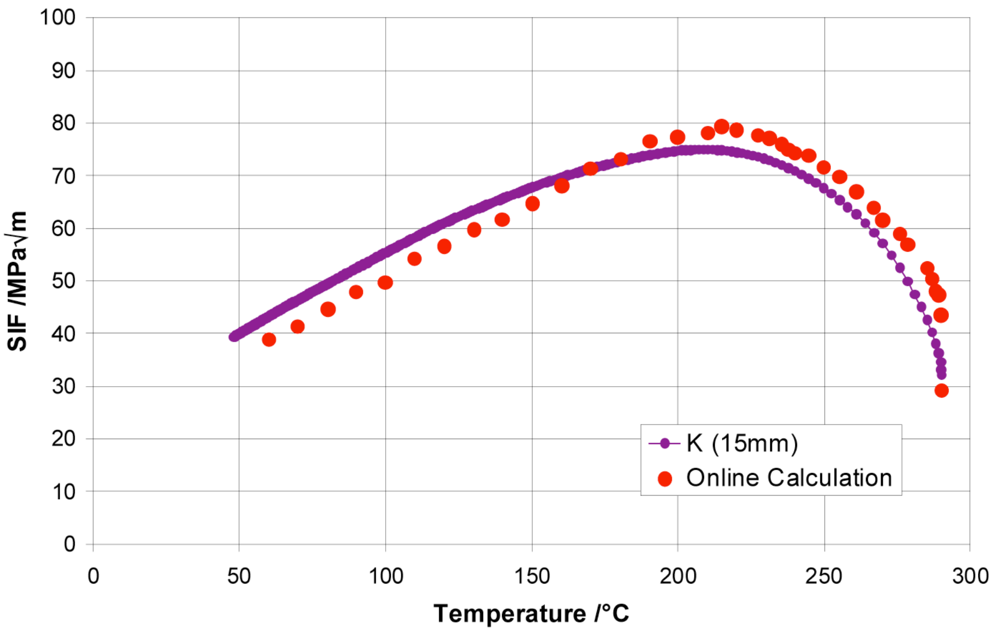
A reset to zero of all measurement data was carried out at the beginning of heating and before reloading up to fracture. Fig. 10 demonstrates the temperature distribution versus time during the transient close to the crack in cross-section C-C. A check that the cooling was homogenous in longitudinal direction was carried out by means of temperature measurements in three cross-sections A-A, C-C, D-D (Fig.4). All temperature curves at the inner and outer wall surface along the cylinder (cross sections) lie very close together. At a depth of 5 mm the temperature is nearly identical in 3 different cross-sections along the cylinder.

Fig. 11 shows the measured longitudinal strain DL3 in section A-A close to the grip over the time during the transient with a decrease of 0.6 mm/m due to PTS followed later by unloading starting at t = 400s. Acoustic emission results did not give any indications of crack initiation during thermal shock.

Crack opening displacements were measured by means of clip gauges in section B – B (cp. Fig. 4). Fig. 12 shows the measurement results of crack opening behavior by means of the clip gauges G1 and G2. G1 at position 0° gives greater values than G2 at position 180°, which is corresponding to the final size of the fatigue crack. A first interpretation of test results is given in [6] and the following chapter 10.



<u>Fig. 8:</u> Tensile load during thermal shock transient PTS



<u>Fig. 9:</u> Comparison of designed load path with online-calculation (MPA)

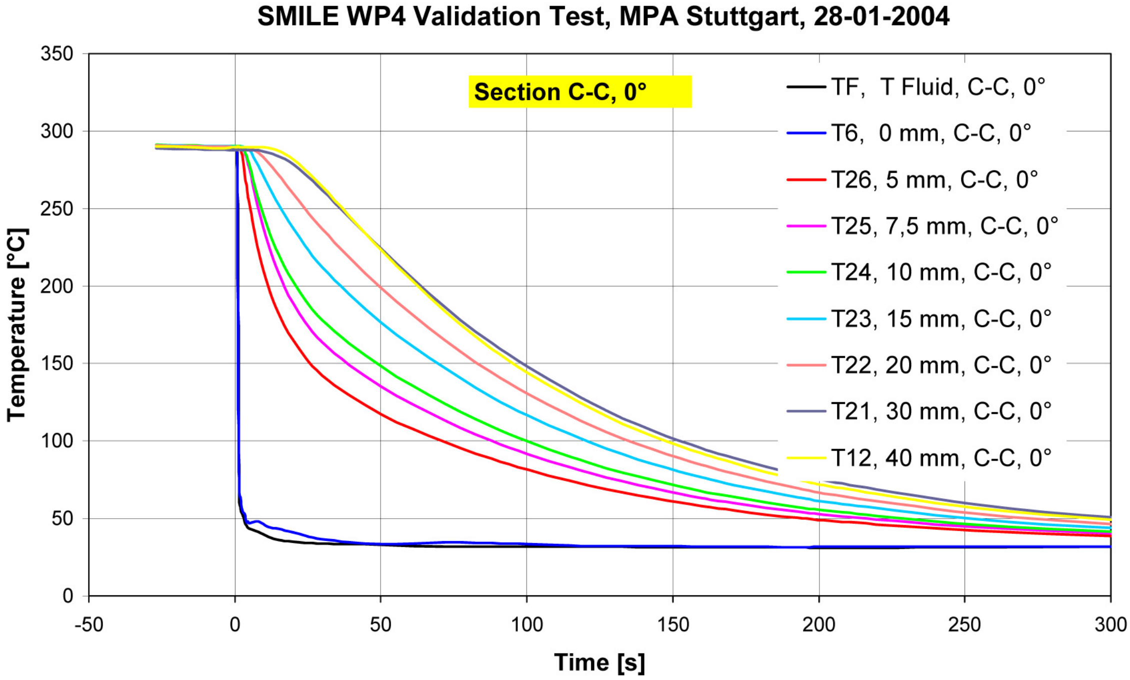


Fig. 10: Temperature distribution versus time over wall-thickness in cross-section C-C

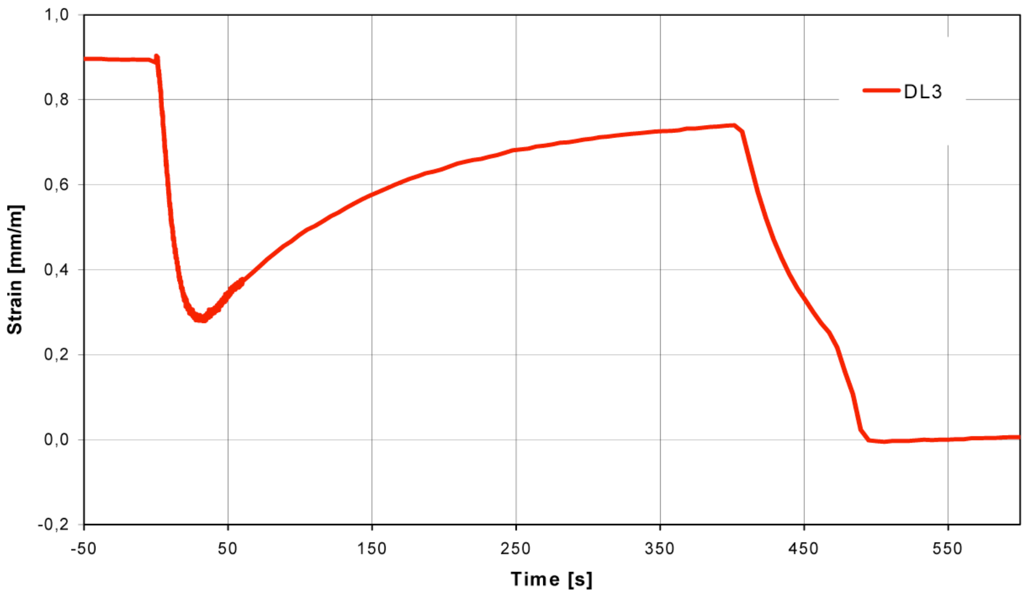


Fig. 11: Measured longitudinal strains DL3 in cross-section A-A during transient and unloading

8.1 Re-loading up to fracture

Re-loading up to fracture was carried out with a linear loading rate of 2 MN/min. A reset to zero of all measurement data was carried out before reloading. The final fracture load was 5.39 MN. The corresponding temperature-level during re-loading ranged from 32°C to 42°C, slightly above RT. Since the lower shelf region of this material remains constant at about 100°C, the re-loading was carried out in the lower shelf region of fracture toughness. The fracture load was significant higher than the crack initiation values of the original material in the lower shelf region, confirming the beneficial WPS effect. The acoustic emission results correspond with the time of fracture. Since the fracture toughness in the lower shelf region remains constant up to about 100°C, re-loading was carried out in the lower shelf region of fracture toughness.

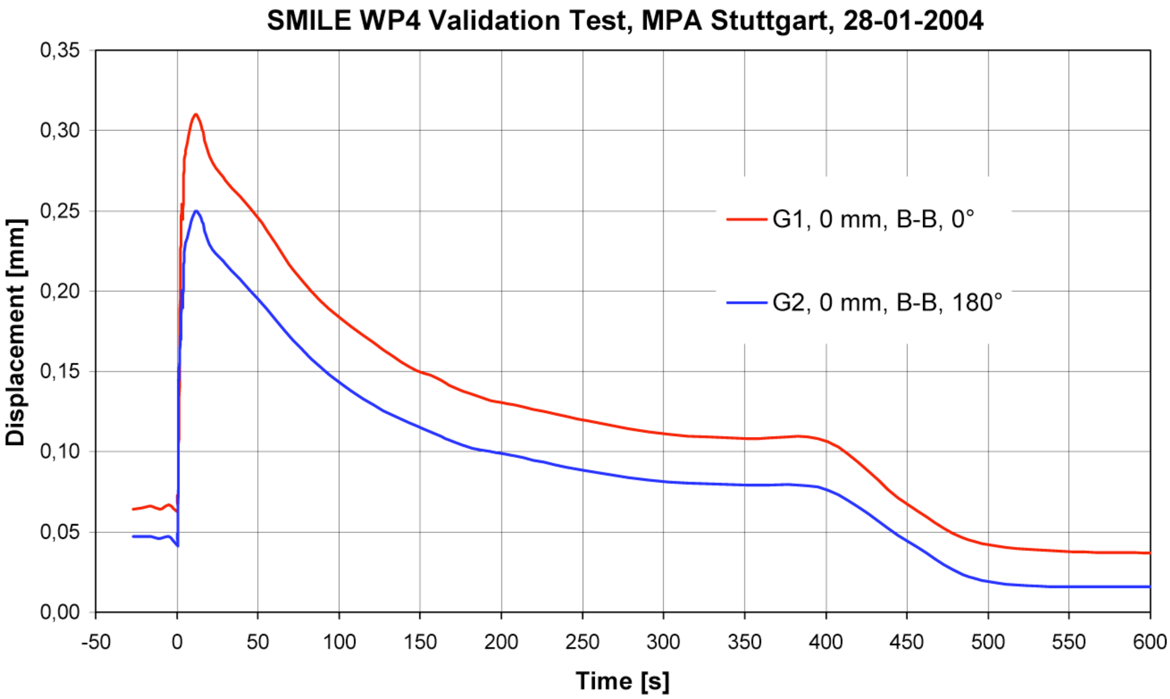


Fig. 12: Measurement of crack opening displacements by means of clip gauges, section B – B, cp. Fig. 4

9 FRACTOGRAPHIC EXAMINATIONS

Following the test, the fracture surface of the test specimen was examined in detail. An overall view is shown in Fig. 13, in which the limit of the fatigue pre-crack and the subsequent fracture is clearly visible. SEM examinations, confirmed that the fracture morphology is predominantly cleavage, as anticipated from the isothermal and WPS tests performed on standard fracture mechanics specimens fabricated from the same material. No isolated cleavage initiation sites were identified, suggesting that this occurred at multiple sites all around the crack tip. Only limited signs of crack tip plasticity and local dimple fracture were found. The overall roughness of the fracture surface was noted.

Fig. 13: Rough fracture surface of specimen

Furthermore metallographic sections confirmed that the fracture occurred on several different planes with frequent instance of multiple cracking. Similar behaviour has been observed on C(T) type specimens tested using WPS type loading cycles, whereas specimens tested under standard conditions show a much smoother fracture surface (and lower toughness).

The post test fractographic evaluation showed that the fracture mode was predominantly cleavage fracture also with some secondary cracks emanating from major crack.

10 ANALYSIS OF THE EXPERIMENT

The interpretation of the WPS experiment on the cracked cylinder is performed by several partners of the project, involving a large panel of analyses:

- Engineering methods and models account for WPS, such as Chell, Chell & Haigh, Wallin …
- Global approaches based on the evaluation of the stress intensity factor (elastic K_I or elastic-plastic K_{IJ}) and the comparison with the fracture toughness of the material
- Local approach of cleavage fracture based on Beremin model and
- Energy approach

The EDF interpretation of the experiment is conducted by 2D axi-symmetrical analyses (due to symmetry reasons) using Code 'Aster' finite element code developed by EDF, including non linear thermal analyses, elastic and elastic-plastic computations.

The first step of the analysis is the evaluation of the temperature field inside the specimen during the experiment and its comparison with experimental data coming from thermocouples located at various locations in the cylinder (cp. Figures 4 and 10). The comparison between numerical results and experimental values showed a good agreement, particularly in the section near to the crack tip (a=15 mm) as described in [6].

The following interpretation of the test is based on the computation of the elastic-plastic stress intensity factor K_J and its comparison with the material K_{Jc} fracture toughness (using Master Curve methodology). The crack depth considered in these analyses is 15 mm. However, in order to validate the analyses (mesh and numerical simulations), an elastic analysis has first been conducted. Two different ways have been used for the evaluation of the elastic stress intensity factor K_I:

- by the 'displacements' method
- using the energy release rate G $\quad K = \sqrt{\dfrac{E_{(T)} G_{(T)}}{1-\upsilon^2}}$

These two analyses brought about that the values of K_J lie very close together validating the model and the simulation.

Afterwards, the elastic-plastic analysis has been carried out using isotropic hardening (large strain and large displacements). The elastic-plastic stress intensity factor K_J, deduced from the computation of the G energy release rate, is compared to the material fracture toughness K_{Jc}, cp. Fig. 14, without any consideration of size effect between 1T-CT specimens used for K_{Jc} experimental investigation and the cylinder specimen. Regarding the K_{Jc} fracture toughness, all experimental data are included in addition to 5 %, 50 % and 95 % Master Curve failure probabilities (T_0 = 140 °C). Fig. 14 shows clearly very significant margins between K_{JC} values and value of the SIF K_J at the cylinder failure, with a high resistance of the cylinder regarding the risk of brittle failure. The evolution, during the experiment, of the elastic-plastic stress Intensity factor K_J on the cylinder is clearly shown:

- The level of pre-loading (K_{WPS}) during cooling is K_{WPS} ∪78 MPa·m$^{1/2}$
- The final failure of the cylinder (K_{FRACT}) is K_{FRACT} ∪84 MPa·m$^{1/2}$
- At room temperature K_{Jc} (1T-CT) = K_{Ic} (1T-CT) < 52 MPa·m$^{1/2}$
- At the cylinder failure $K_{FRACT} >> K_{Ic}$ (1T-CT)
- At the cylinder failure $K_{FRACT} > K_{WPS}$

	K_{FRAC}	K_{WPS}	K_{FRAC}/K_{WPS}	K_{FRAC}/K_{Jc}
Failure of cylinder (no size correction)	84	78	1.08	1.62

By comparing the respective behavior of 1T-CT specimens and cracked cylinder, the beneficial effect of warm pre-stress is shown, by inducing a significant increase of the resistance of the cylinder regarding brittle failure initiation. This conclusion is clearly underlined regarding the influence of the size effect correction between the 1T-CT specimens and the cracked cylinder, which is described in detail in [6]. Further interpretation based on the result of other computations will be done in future. Also fracture mechanics assessment based on physical initiation characteristics will be carried out.

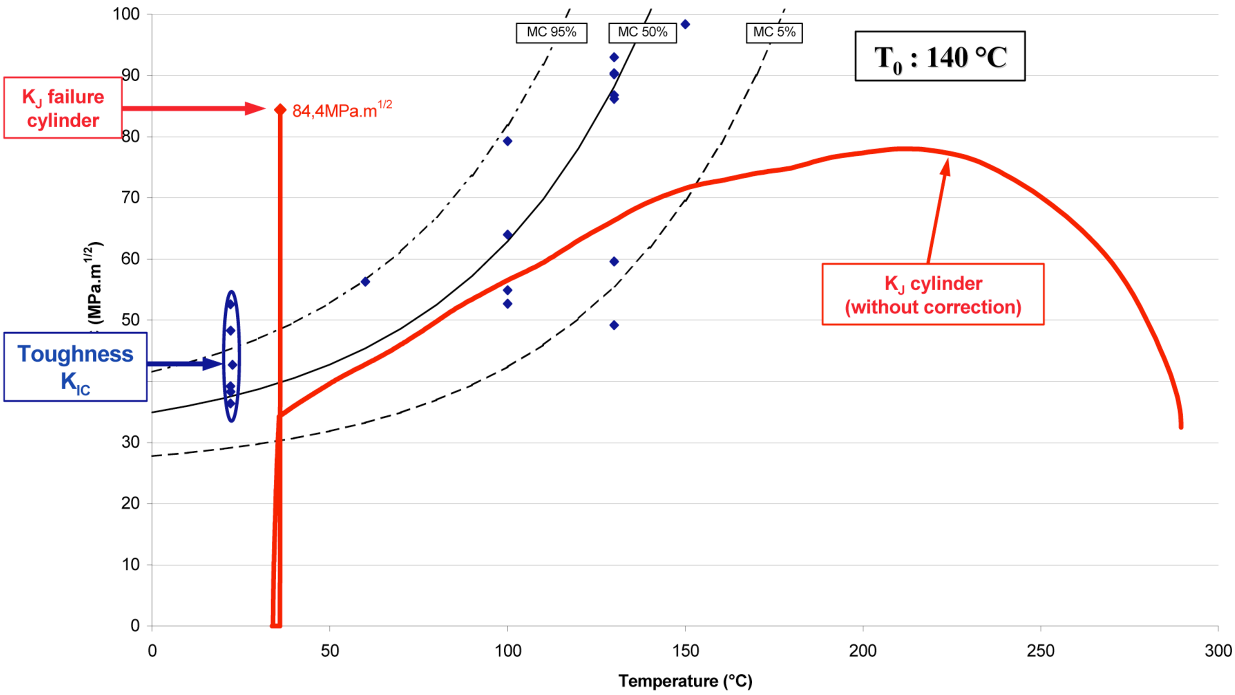


Fig. 14: Comparison between K_J and K_{Jc} (without size correction)

11 CONCLUSION

The experimental results of a PTS type transient experiment on a cylindrical specimen subjected to WPS- loading are described. The test specimen consists of a cylindrical thick walled specimen with a thickness of 40 mm and an outer diameter of 160 mm, provided with an internal fully circumferential crack with a depth of about 15 mm. The specified load path comprises Load-Cool-Unload-Fracture (LCUF).

No crack initiation occurred during cooling (thermal shock loading) although the loading path crossed the fracture toughness curve in the transition region. The benefit of the WPS-effect by final re-loading up to fracture in the lower shelf region was shown clearly. The corresponding fracture load during reloading in the lower shelf region was significantly higher than the crack initiation values of the original material in the lower shelf region.

A first numerical analysis of the test is in good agreement with the experimental load level of failure, showing significant margins due to the WPS effect, with a higher resistance of the cylinder regarding the risk of failure.

12 ACKNOWLEDGEMENTS

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