

HOLD TIME EFFECTS OF STABILIZED AUSTENITIC STAINLESS STEELS – TO BE TRANSFERRED INTO PRACTISE FROM EXPERIMENTAL FATIGUE INVESTIGATIONS

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ABSTRACT

Experimental laboratory testing on relevant German NPP primary piping niobium stabilized stainless steel material (1.4550, X6CrNiNb1810mod) shows a beneficial effect when considering hold times between fatigue cycles.

During normal operation PWR components like the surge line or spray lines are exposed to only few fatigue relevant temperature loadings. Introduction of additional periods of elevated temperature without additional loading is one experimental approach to simulate plant behaviour more realistically. Beyond that the introduction of a potentially beneficial effect of hold times is foreseen in the framework of piping design of the German KTA in general.

Within the publication recent experimental results of laboratory investigations will be presented. These results will be used to develop an engineering approach to take beneficial hold time effects into account in terms of increasing component's predicted design lifetime. Obtained results will be used to derive an influence function taking hold time effects into account analytically. Finally an example will be presented showing the impact of the introduction of hold time effects on fatigue assessment of components. Within this component based example the beneficial effect of hold times will be discussed and the potential consequences to standard fatigue assessment procedures will be considered.

INTRODUCTION

Since several years environmentally assisted fatigue (EAF) is one topic of interest in the context of material sciences in the framework of designing and evaluating NPP components' lifetime.

The topic has been evident at least since publication of the US-NRC Regulatory Guide 1.207 in 2007, defining a guideline for evaluating fatigue analyses incorporating the possibility of life reduction of metallic components due to effects of the LWR coolant environment. Within this framework the referenced ANL report NUREG/CR-6909 by Chopra et. al. defines a new and comprehensive set of laboratory fatigue data including in air as well as under LWR conditions for relevant material grades. Beyond that, it derives an empirical numerical correction factor, the so called F_{en} , out of this database.

In spite of the fact that the application in the framework of US-NRC Regulatory Guide 1.207 is limited to new reactors builds and licence renewal processes only, consideration of EAF to nuclear reactors being currently in operation is state of the art and practice in Germany. Generally, taking into account the phenomena of EAF is basis in regulatory frameworks like ASME or KTA.

Laboratory investigations have shown, that LWR coolant environment has a lifetime reducing influence on fatigue behaviour of metallic components under some defined conditions in general. Anyhow, a concluding quantification of the phenomena and full scientific understanding of the phenomena including final proof of transferability from laboratory conditions to plant like conditions is still focus of current R&D activities. Most of existing laboratory investigations have in common, that parameters influencing component's lifetime negatively have been considered only in terms of conservative calculations. On the other hand, there are other parameters which influence the component's fatigue lifetime in a positive manner. As such positive effects are neglected so far, taking into account EAF tend to become over

conservative leading to oversized components. Therefore, positive effects should be considered as well in the framework of a comprehensive and detailed analysis making sure not to overdesign components.

When taking a closer look on the operational behavior of primary circuit components, fatigue loading is mainly defined by long steady-state periods with no significant changes in the loadings and by normally short outage periods with no thermal loading. For example fatigue of a PWR surge-line is mostly caused by short in-surge and out-surge events during start-up and shut-down of the plant. Normal operation transients do not cause fatigue relevant events in the surge-line due to low stratification and thermal transients. Fatigue of PWR spray-lines is primarily generated by very few spray-events during a one-year period of operation. Spray events are mainly caused by significant load ramps. Subsequently the fatigue status is controlled by long periods with no fatigue relevant loading at operating temperature and few additional loading patterns in between.

Anyhow, no quantifications of these hold time effects have been published in recent years. Within this publication an engineering based approach will be developed to quantify the hold time effect based on literature and published data. On the basis of a practical example the influence of hold time effects will be quantified in an engineering approach.

FROM OPERATIONAL CONDITIONS TO LABORATORY EXPERIMENTS

In recent years some R&D activities have indicated already, that there might be benefits to the fatigue lifetime of components when taking operational-like transients into account. By means of this, it is worth to take a closer detailed look to long term fatigue evaluation by intensively analyse temperature measurement data.

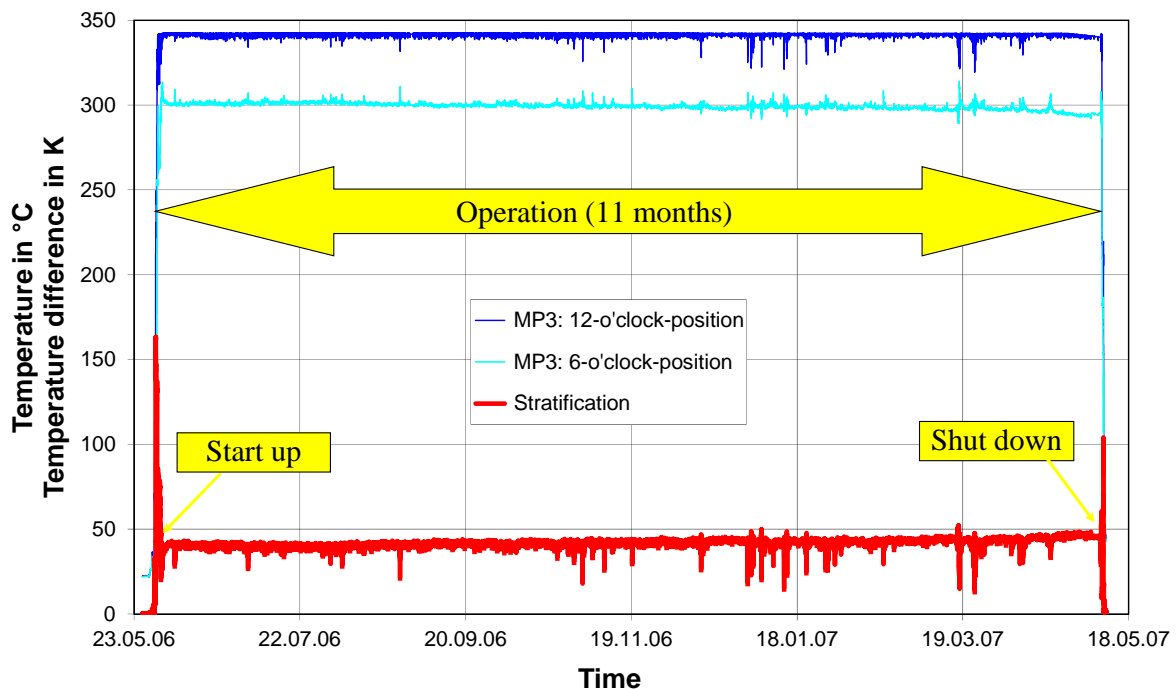


Figure 1: Temperature Measurements of a Surge Line.

Such an evaluation is shown in Figure 1 where a one-year representative temperature measurement history at the surge line of a PWR is depicted. Relevant loadings of PWR surge lines are caused by in-surge and out-surge events of coolant medium from the pressurizer into the main coolant line or vice versa. These events occur when the main coolant pumps are turned on/off, i.e. during start-up respectively

shut-down of the NPP. It should be noted explicitly that during the eleven months operation phase of the NPP, there are no fatigue relevant load changes. Hence, there is a hold-time of eleven months between fatigue relevant loading cycles. This is only one example as the operation of PWR spray nozzles are observing comparable long hold periods und normal operation conditions as well. Taking these aspects into account an R&D programme was initiated to consider the effect as a whole. On the one hand an experimental test program has been accomplished to investigate hold time effects in laboratory conditions and taking operational conditions into account. Key finding of this activities are briefly described in the following section. Beyond that, additional activities taking a closer look to the impact of hold time effects to numerical fatigue assessment of components have been initiated which will be described in the following.

EXPERIMENTAL INVESTIGATIONS

For experimental investigations smooth round bar specimens were turned from longitudinal samples of relevant qualified piping material. Tests were performed in MTS 100 kN and 250 kN rigs with precision alignment grips and MTS 653 furnace. Alignment of load train was adjusted with strain gauged specimens according to the ASTM E 1012-05 procedure. Strain controlled low cycle fatigue tests were performed according to the ASTM E 606 procedure.

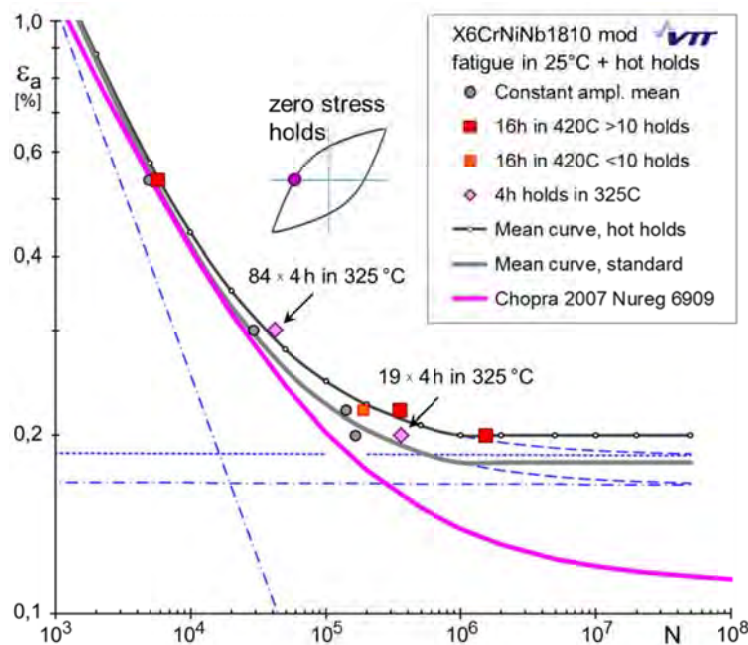


Figure 2: Extension of Life Due to Hot Holds.

Results of experimental investigations have been published in scientific publications at the PVP conference (e.g. PVP2014-28465 and PVP2015-45098) dealing with effects of hold times on fatigue life of stainless steel in simulated operational conditions. In terms of this experimental test program fatigue of Niobium stabilized austenitic stainless steel (X6CrNiNb1810 mod) has been comprehensively studied using specimens extracted from a relevant NPP primary piping material batch. Accelerated tests simulating the effect of normal operation between fatigue relevant transients reveal consistent hardening behaviour, which can be linked to extension of life. Detail mechanisms responsible for extension of life have not been identified, but for engineering purposes they can be modelled as thermally activated

processes. Figure 2 clearly demonstrates extension of life due to hot holds. The effects on the stress response can also be seen in Figure 3. For more detailed information concerning relevant aspects like applied experimental methods, effect of test temperature, strain rate and hold hardening with variable amplitude strain the reader may be referred to mentioned PVP publications. Also influence of PWR primary water environment has been addressed in these previous papers.

Anyhow it should be noted, that hardening occurs irrespective in which phase of the cycle the hold is introduced. The extent of hardening does not depend on the hold position. Hardening occurs in all temperature combinations between room and normal operation temperatures, but it is more effective when hold occurs in high temperature for long time and when the preceding cyclic strain occurred in low temperature resulting to large cumulative cyclic strain. In other words, when some fatigue usage is consumed (\rightarrow driving force), thermal activation is provided, as it is during long term operation of a NPP.

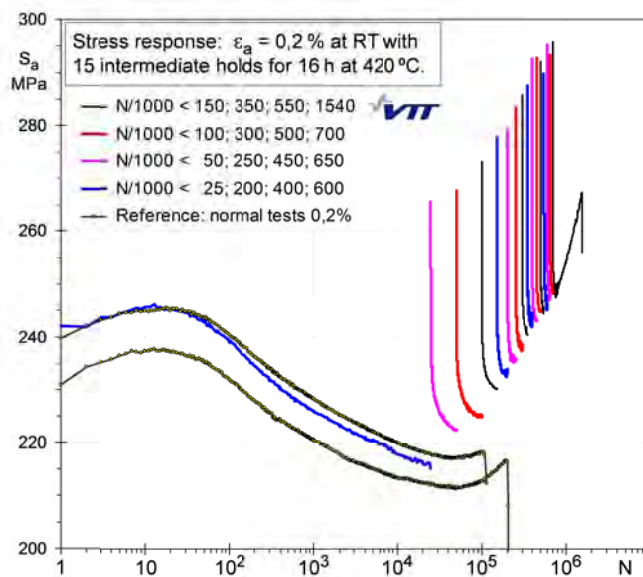


Figure 3: Effect of Holds on Stress Response.

Experimental investigations have shown that hold time effects have a positive influence on fatigue lifetime of austenitic stainless steel materials.

NUMERICAL MODEL

The general beneficial effect of hot holds on the fatigue curve is shown in Figure 2. To describe the effect, the following approach is made using a beneficial factor in terms of strain (stress) amplitude:

$$\varepsilon_{a,hold\ time} = \varepsilon_{a,standard\ test} \cdot f_{hold}(N) \quad (1)$$

The effect is insignificant at cycles less than about 10^4 (low cycle fatigue range). But at high cycles, there is a distinct improvement of the curve. The beneficial factor beyond the endurance limit ($N \geq 10^6$) can be read from the equations of the “Basquin lines” for hot hold tests and standard tests (PVP2011-57942):

$$f_{hold}(N \geq 10^6) = \frac{0.188}{0.168} = 1.12. \quad (2)$$

Based on the available data, at $N = 10^4$, no hold-time effect is assumed:

$$f_{hold}(N < 10^4) = 1.0. \quad (3)$$

So, the following proposal is introduced for the influence function, producing a straight line in a log-log coordinate system:

$$f_{hold}(N) = C \cdot N^\alpha . \quad (4)$$

Considering Figure 2, one gets $C = 0.7972$ and $\alpha = 0.02461$.

This leads to the preliminary influence function as shown in Figure 4:

$$f_{hold}(N) = \begin{cases} 1.0 & \text{for } N \leq 10^4 \\ 0.7972 \cdot N^{0.02461} & \text{for } 10^4 < N \leq 10^6 \\ 1.12 & \text{for } N > 10^6 \end{cases} \quad (5)$$

This influence function is a first approach to describe the beneficial hold time effect in terms of an increasing endurance limit based on the available relevant test results. As the factor is applied to the strain (stress) amplitudes and as the fatigue curves are strongly non-linear (e. g. Figure 2), the impact on the results in terms of cycles is essentially larger than on the strain (stress) amplitudes.

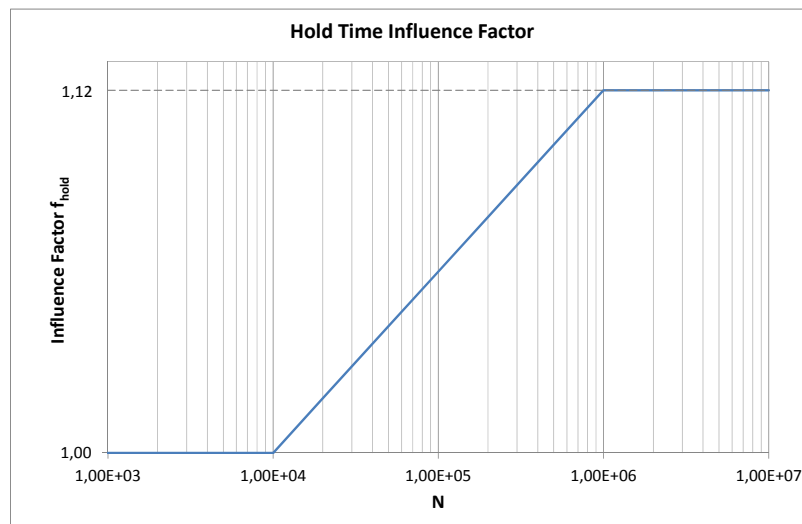


Figure 4: Hold Time Influence Factor for Design Stress Intensity.

NUMERICAL APPLICATION

Being aware of the preliminary character of the defined influence factor and only to show the possible impact on fatigue results, in this section the hold time effect is applied to the fatigue evaluation of power plant components made of the austenitic stainless steel 1.4550, e.g. surge lines and spray lines in PWR.

The first step is to define an adjusted fatigue design curve under consideration of the influence factor from Figure 4. In Figure 5, the effect is exemplarily shown for the fatigue design curve for austenitic steels 1.4550 and 1.4541 at temperatures greater than 80 °C as used in the German KTA code 3201.2 revision 2013.

The impact of the hold time effect to the fatigue usage is exemplarily shown for the load counting list of a typical NPP primary circuit component. This load counting list is a result of a fatigue analysis for this component and describes the relationship between cyclic load and fatigue usage, see Table 1. The cyclic load is given in Table 1 as temperature stratification, measured at this component, and the corresponding

stress amplitude. The fatigue usage is represented by the number of allowed cycles as read from the fatigue design curve with respectively without hold time effect. In this example, the reduction in fatigue usage per cycle is up to one third in the lowest temperature class, while no reduction will occur in the maximum temperature class. The maximum possible reduction has to be expected in direct vicinity to the endurance limit and can reach values greater than 1000. So, the resulting overall reduction is strongly dependent on the component specific load history.

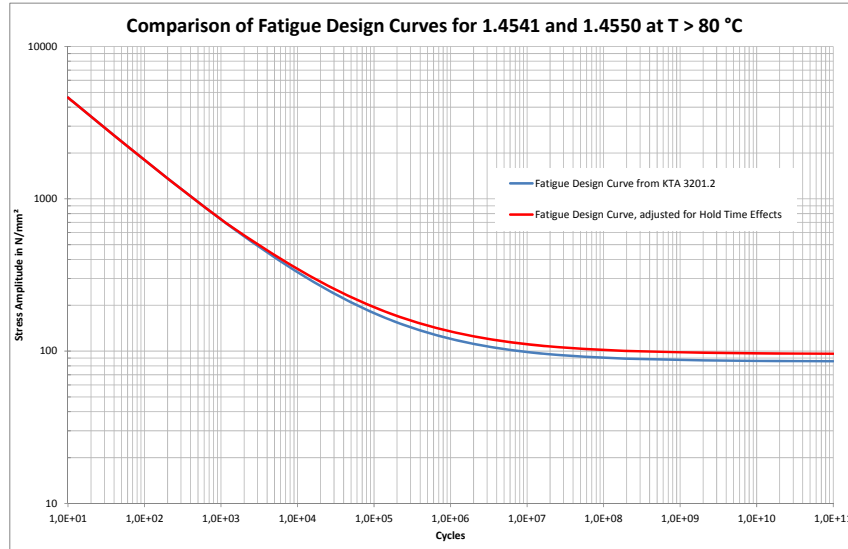


Figure 5: Hold Time Effect applied to Fatigue Design Curve for Austenitic Steels from KTA Code.

Temperature Stratification (Temperature Class)	Stress Amplitude in N/mm ²	Allowable N° of Cycles from KTA Design Curve (without Hold Time Effect)	Allowable N° of Cycles from Adjusted Design Curve (with Hold Time Effect)	Reduction in Fatigue Usage per Cycle from Hold Time Effect
$70 \leq \Delta T < 100$ K	233	33497	44315	-32,3%
$100 \leq \Delta T < 130$ K	305	13000	15636	-20,3%
$130 \leq \Delta T < 160$ K	498	2911	3112	-6,9%
$160 \leq \Delta T < 180$ K	725	1029	1032	-0,3%
$180 \leq \Delta T < 200$ K	992	452	452	0,0%

Table 1: Impact of Hold Time Effect on Fatigue Usage.

CONCLUSION

Fatigue performance of Niobium stabilized austenitic stainless steel (X6CrNiNb1810 mod) has been studied using specimens extracted from a NPP primary piping material batch. In this context, transferability of laboratory test results has been addressed. Good fatigue performance was demonstrated in the room temperature air condition, which is specified for determination of ASME III design curve. Our data is in line with the 2013 revision of the German KTA design curves.

Temperature and strain rate effects are nowadays generally considered for fatigue usage in hot water environment. In addition, they should not be ignored as contributors to design factors also in air

environment. Actually our data (not presented here, see PVP2014-28465) indicates that notable part of the measured “environmental effects” F_{en} are not due to water, but other test parameters used in hot water.

Another transferability challenge rises from thermally activated hardening, relaxation of internal stresses and seemingly also recovery of deformation induced damage during hot holds. Laboratory tests simulating the effect of normal operation between fatigue relevant transients consistently reveal stress strain responses different to continuous standard tests and good evidence is obtained that this can be linked to extension of life. A correlation between life extension and number or duration of holds is observed. However, in this paper presented numerical model is based on tests with small amounts of short duration holds.

Effects of environment, temperature and loading patterns (including hold times at operational temperatures) shall be all considered together with the design procedure. Only doing so, we can maintain transferability of fatigue data to NPP component design and fatigue usage assessment.

As an engineering approach to account for the hold time effect in fatigue evaluation, an influence factor to the fatigue curve is proposed. Based on ongoing current research activities the numerical model might be revised when further relevant data is available. A numerical example is shown to have an impression of the possible impact of this effect to fatigue results. As the strongest reduction in fatigue usage is found at load amplitudes next to the endurance limit, while no reduction occurs at high amplitudes, the impact of the hold time effect on fatigue results is strongly dependent on the component specific load history.

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