In-Situ Characterization of Damage Evolution in Welded Aluminum Alloy Joints during Cyclic Deformation in the VHCF Regime by Means of Nonlinear Ultrasonics and Thermography

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Abstract: The ultrasonic fatigue testing system (UFTS) with working frequencies of 18-21 kHz is nowadays an established method for studying the cyclic behavior of materials at very high numbers of cycles ($N_f > 10^7$). Latest research activities in the Very High Cycle Fatigue (VHCF) area focus on damage mechanisms of various materials with and without defects. Defects are mainly analyzed at a microstructural level, such as non-metallic inclusions in high strength steels or pores in cast alloys. In this respect the significance of crack initiation in quasi defect-free materials and early crack propagation in defect-afflicted materials is discussed. However, a study of complex structures with macroscopic defects deriving from manufacturing processes were not yet part of the ongoing research activities and will therefore be discussed in this paper using the example of welded aluminum alloy joints.

In the study presented welded samples were tested by means of UFTS. Crack initiation and crack growth were characterized by means of nonlinear ultrasonics and infrared thermography. The nonlinear ultrasonics technique allows for a registration of the formation of higher harmonics at frequencies exceeding the fundamental frequency (~ 20 kHz) due to nonlinear elastic material behavior and/or so-called contact acoustic nonlinearity [1]. With the help of a thermal imaging camera the temperature gradient of the sample surface and thus the local damage evolution in the sample can be evaluated during fatigue tests. The results of both experimental methods applied - the nonlinear ultrasonics and the thermography - are compared and discussed with regard to the influence of macroscopic and microscopic notch effects in the welded joints and their effect on the life contribution of crack initiation and crack growth phase within overall fatigue life in the VHCF regime.

Introduction

Current research activities on fatigue behavior at very high cycles are mainly focused on fundamental damage mechanisms preferably in macroscopically homogeneous materials by means of small laboratory samples with polished surfaces. In this context, a wide range of influencing parameters such as experimental setup, environmental conditions, testing frequencies, manufacturing of samples, monotonic predeformation or shot peening were discussed in detail with respect to their influence on the fatigue behavior at very high cycles (see amongst others [2-3]). However, welded joints with heat-affected zone, geometrical notches at the transition area from base material to weld seam and process-related weld defects (e.g. pores, hot cracks or incomplete fusions) are complex inhomogeneous structures and to a certain extent not compatible with the special requirements of the ultrasonic fatigue testing system (UFTS) regarding size and geometry of the samples. Because of this, studies of the fatigue behavior of welded structures at very high cycles are only recently part of the current research activities.

One of these activities is the work of Xiaohui et al. [4] regarding the fatigue behavior of butt welds out of EH36 steel ground flush in the super-long life regime. Experimental results indicated that fatigue fracture in the base material and in the weld seam still occur at 10^8-10^{10} cycles. Xiaohui et al. observed that fatigue crack often started in the fusion zone even if larger defects existed in the weld seam area. The fatigue strength of the base material was much higher compared to the weld seam. In the work of He et al. [5] shot-peened welded joints made out of Q345q steel were tested by means of an UFTS with a resonant frequency ~20 kHz at a stress ratio R = -1 at room temperature and ambient air. The results show that the fatigue strength of samples representing the weld seam are 60 % lower compared to the base material. Shot-peened joints showed a significantly improved fatigue strength in the VHCF range with crack initiation at inner defects in the weld seam. The VHCF behavior of welded samples out of aluminum alloys depend on the geometrical notch of the weld seam between base (BM) and filler material, process-related structural notch effects caused by a strength gradient in the heat-affected zone (HAZ) and particularly on local defects and imperfections in the weld seam [6-8]. With the majority of defects being located in the interior of the critically loaded volume fraction, damage evolution starting from any such defect cannot be characterized in-situ with classical methods regarding crack initiation and crack growth, especially while using an UFTS.

A promising technique to introduce nondestructive damage monitoring to UFTS are nonlinear ultrasonics introduced by Kumar et al. [9-11]. He used the feedback signal of an UFTS to characterize the fatigue damage accumulation based on the changes in the nonlinear ultrasonic parameter. An extensive review of the nonlinear ultrasonic technique is given by Jhang [1]. Fatigue damage evolution up to very high cycles was studied for the precipitation-hardened Al-alloy AA 6082 in the condition of maximum strength and hardness T651, the cast Al-alloy AS7GU and the die-cast magnesium alloy AXJ530 [9-11]. The studies demonstrated, that the initiation and growth of a crack lead to an increase of the nonlinear ultrasonic parameter and to a decrease in the resonance frequency.

The use of thermography to characterize local damage evolution in a volume sample or structural component is state of the art (e.g. for nondestructive inspections of automotive parts [12]). According to Ranc et al. [13], who studied the thermal effects associated with crack propagation during very high cycle fatigue test with an infrared camera, the increase of temperature at the crack during fatigue testing is significant but also rather localized. On the basis of their experimental results for a high-strength steel together with a thermo mechanical model Ranc et al. showed that the propagation stage of the crack constitutes only a small part of the lifetime for specimens failed in VHCF range. In the present study both nonlinear ultrasonics and thermography are used to characterize the crack initiation and crack growth of welded aluminum joints during cyclic loading up to the range of very high cycles by means of an ultrasonic fatigue testing system.

Material data and experimental setup

Fatigue tests were carried out using welded samples out of the precipitation-hardened Al-alloy EN AW-6082 T651, the work-hardened Al-alloy EN AW-5083 H111 and the filler material S Al 5183. The chemical composition and the mechanical properties are given in Table 1.

Table 1. Chemical composition [mass-%] of the Al-alloys and mechanical properties.

Material	Mg	Mn	Si	Fe	Zn	Cu	Cr	Ti	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
AlMgSi 1 (AW-6082)	1.03	0.56	1.05	0.20	0.03	0.08	0.02	0.02	297	325	17
AlMg 4.5 Mn (AW-5083)	4.71	0.58	0.26	0.35	0.05	0.05	0.10	0.03	160	301	23
AlMg 4.5 Mn 0.7 (S 5183)	4.80	0.66	0.05	0.17	0.01	0.01	0.07	0.08	130	275	18

The weld seams were realized as MIG-welded double-V butt joints by using blanks with a thickness of 6 mm and a welding wire with a diameter of 1.5 mm. Details about geometry, Vickers hardness and microstructure of the welded samples are described elsewhere [6-8]. Fig. 1a depicts a micrograph across the weld seam with clearly identifiable pores marked with arrows. In addition Fig. 1b depicts clusters of pores with different sizes and sporadic incomplete fusions predominantly arranged in the center of the seam.

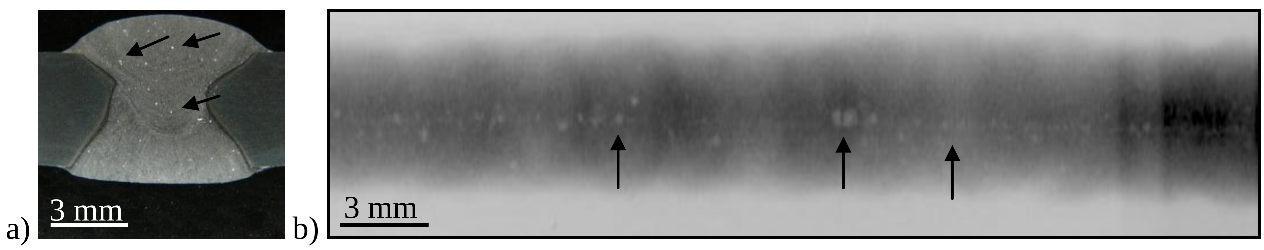

Fig. 1. a) Micrograph across the weld seam and b) x-ray photography in top view with process-related weld defects such as pores and incomplete fusions (marked with arrows).

Fatigue samples were manufactured out of the welded blanks in two different cut out positions: heat-affected zone out of AW-5083 and AW-6082 (HAZ) and weld seam out of S 5183 (WS), as depicted in Fig. 2 a. The resulting cross-sections are shown in Fig. 2 b. Due to the need of symmetrical geometries for the UFTS all samples surfaces were trimmed. The flat welded geometry of the samples is shown in Fig. 2 c.

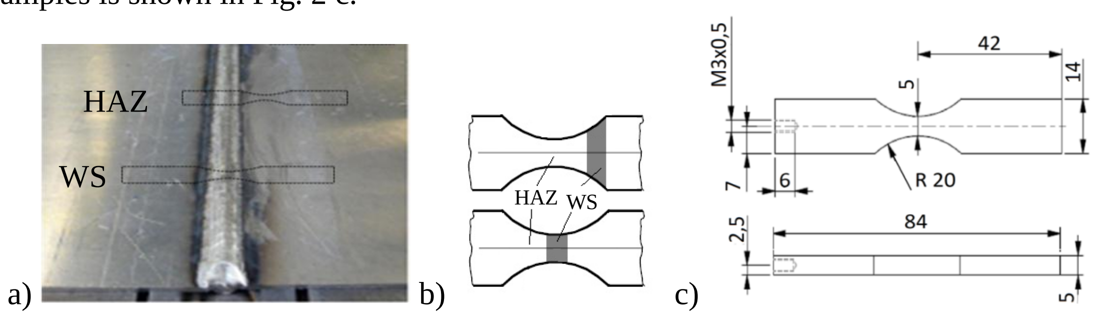

Fig. 2 a) Welded blank with cut out positions (WS and HAZ) marked with dashed lines, b) resulting cross-sections of the fatigue samples and c) trimmed sample geometry.

Fatigue tests were performed at a stress ratio R = -1 by means of a standard ultrasonic fatigue system with a test frequency of ~20 kHz. All samples were electro-chemically polished prior to fatigue testing in order to exclude the effect of micro notches other than those induced by the welding process. In order to avoid heating of the specimens as a result of the high-frequency loading, cycles are given in pulse/pause sequence of 400/1600 ms with additional air cooling of the samples. Increase of temperature as a possible result of damage evolution (crack initiation and/or crack growth) was measured by means of an infrared camera FLIR A20 which is triggered by the process control unit of the UFTS and synchronized with the pulse sequence. Due to the thermal inertia, thermographs were taken with a delay of 30 ms referred to the pulse to measure the maximum temperature. The system setup for the nonlinear ultrasonics technique consists of a digital oscilloscope and a personal computer including data acquisition software (realized in LABVIEW) which analyzes the sinusoidal wave originally obtained by the ultrasonic transducer and measured through the vibration gauge. A schematic overview of the complete experimental setup is depicted in Fig. 3. The feedback signal of defined amplitudes includes, in turn, the damage state of the sample being tested as a function of load cycles and is registered and analyzed by the individual designed data acquisition program including a fast fourier transformation (FFT)-analysis.

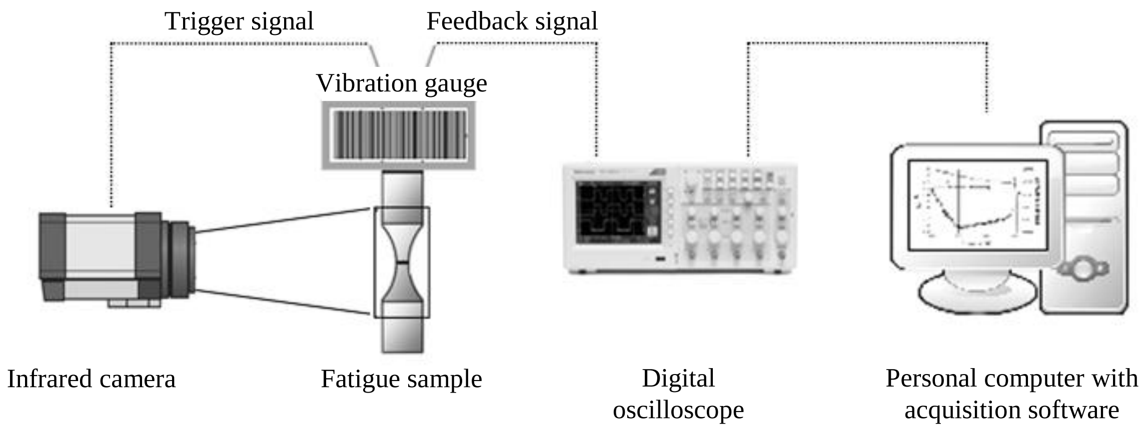

Fig. 3. Experimental setup with infrared camera with focus on the gauge length of the sample, lower section of the UFTS power train and nonlinear ultrasonic system (oscilloscope, PC and data acquisition software).

As indicator of the fatigue damage the so called nonlinear parameter β is used. The parameter is defined by Eq.1 and is based on the amplitudes of the first and second harmonics a_1 and a_2, the fundamental frequency ω_o, the ultrasonic wave velocity c and the propagation distance x.

$$\beta = \frac{8 \cdot c^2 \cdot a_2}{\omega_0^{\ 2} \cdot x \cdot a_1^{\ 2}} \qquad (1)$$

In general, an increase of β as well as a decrease of the resonance frequency f_R indicate crack initiation. In the following, the relative nonlinear parameter β_{rel} ($\beta_{rel} = \beta/\beta_0$) with β_0 as value of the undamaged material is used to describe damage evolution. More details about the physical principal and the detailed correlation between higher harmonics and nonlinear material behavior are given by Kumar et al. [9-11].

Results and discussion

Nonlinear parameter and resonance frequency of samples out of the weld seam (S 5183) tested at different stress levels as well as corresponding fracture surfaces are presented in Fig. 4. All samples show interior crack initiation at weld defects (compare Fig. 1). It could be determined that crack initiation started at incomplete fusions (marked with white arrows in Fig. 4 a-c) and fatigue crack propagated towards clusters of pores. Dashed lines separate the fatigue from the static fracture area. The increase of β_{rel} right from the start of the tests a) and b) indicates an early crack initiation and crack growth. Different intensities in the increase of β_{rel} of these two samples can be connected to different crack growth rates which stands in good correlation with the different stress levels. In samples d) and e) crack initiation occurred at incomplete fusions with a rather small content of area compared to the overall cross section (Table 2).

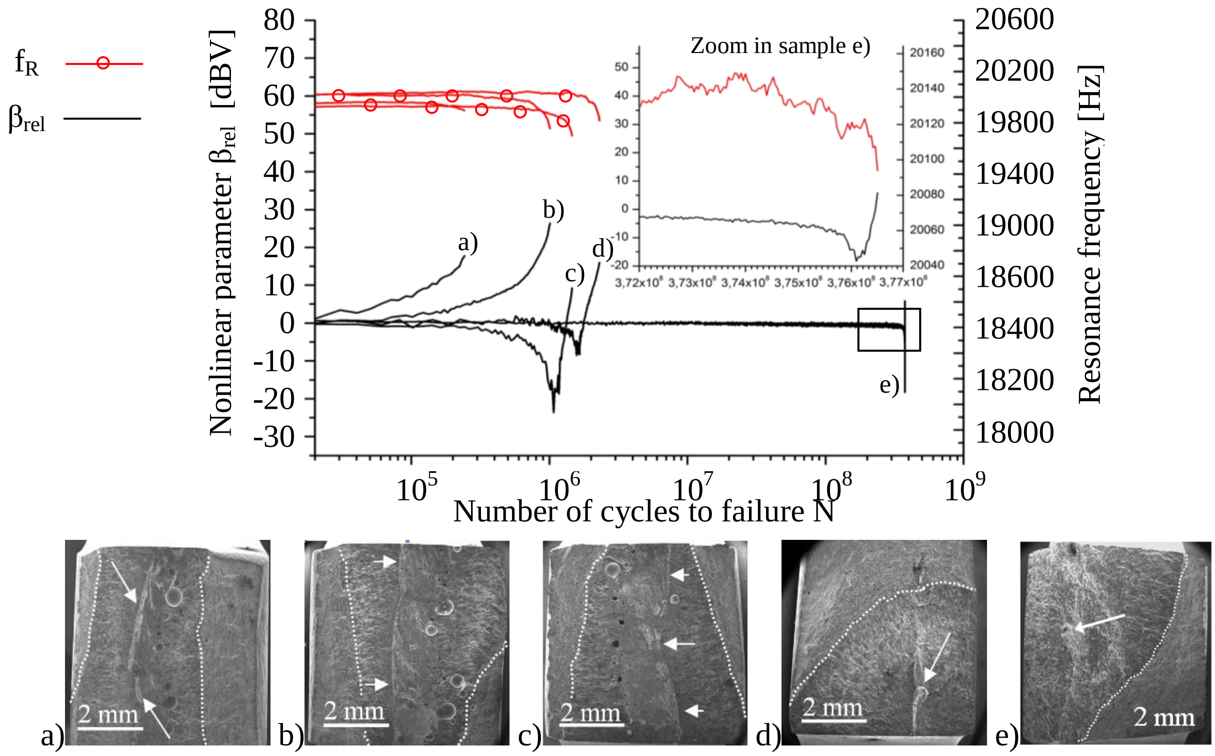

Fig. 4. Relative nonlinear parameter β_{rel} and resonance frequency f_R during fatigue tests and corresponding fracture surfaces of weld seam samples S Al 5183 with a) $\Delta\sigma/2$ = 70 MPa, b) $\Delta\sigma/2$ = 55 MPa c) $\Delta\sigma/2$ = 40 MPa d) $\Delta\sigma/2$ = 55 MPa and e) $\Delta\sigma/2$ = 80 MPa.

Sample d) reached a higher number of cycles to failure without the presence of pores compared to samples b) and c) at nearly the same stress level of 55 MPa. A comparison of load cycles to failure and tested stress levels of sample d) with e) containing comparable defect areas (Table 2) shows that the size and the position of the crack initiating defect e.g. in the subsurface area (sample d) or in the center (sample e) of the cross section, have a significant influence on the overall fatigue life of the welded samples presented.

Table 2. Distribution of surface area of incomplete fusions (IF) and pores.

Sample No.	Area Pores [mm²]	Area Pores [%]*	Area IF [mm²]	Area IF [%]*	Total Area [mm²]	Total Area [%]*
a	0.61	2.4	0.49	1.9	1.11	4.4
b	0.97	3.9	0.90	3.6	1.87	7.5
c	0.95	3.8	1.01	4.0	1.96	7.8
d	0	0	0.26	1.0	0.26	1.0
e	0.09	0.4	0,09	0.4	0.18	0.8

(*corresponding to cross section)

The reason for the decrease of β_{rel} in samples c-e prior the overall failure has yet to be investigated. Run out samples did not contain any such detrimental defects and are therefore disregarded in the given study. Thermographs presented in Fig. 5 a-e show the temperature evolution on the surface of a sample representing the HAZ AW-6082 at a stress amplitude of 70 MPa. Surface temperature at the beginning of the test was 20 °C and already at 16 % of the overall fatigue life an increase to 28 °C could be noticed, which slowly increased to a value of 32 °C at 79 %. Fig. 5 c-e depicts the maximum surface temperature evolution with 47, 55 and 93 °C for 94, 99 and 100% of fatigue life, respectively. The drastic increase of temperature shortly before the end of the test is most likely related to a start of the final rupture of the specimen while the minor and steady increase at the beginning (between Fig. 5 a and 5 b) could be a result of microstructural changes or early microcrack growth. Whether early fatigue damage evolution, such as a change in dislocation structure and density, nucleation of fatigue voids or a coalescence of microcracks [14-15] can be directly correlated to the different stages of temperature increase for the given material setting will have to be proven by future studies including electron microscopy and ultrasonic fatigue testing.

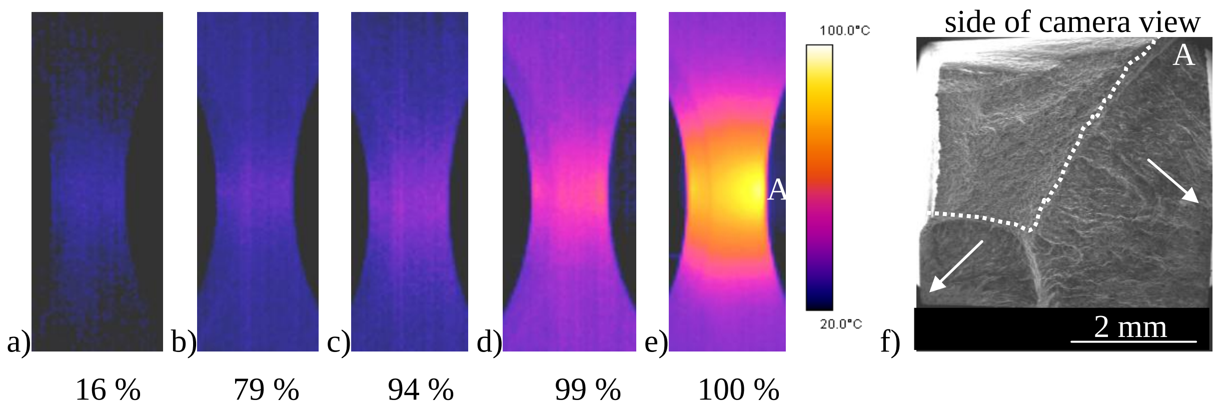

Fig. 5. Temperature fields on specimen surface of EN AW-6082, HAZ at stress peak and percentage of the overall fatigue life for $\Delta\sigma/2 = 70$ MPa at a) $N = 8.9 \cdot 10^5$, b) $N = 4.37 \cdot 10^6$, c) $N = 5.13 \cdot 10^6$, d) $N = 5.42 \cdot 10^6$, e) $Nf = 5.48 \cdot 10^6$ and f) corresponding fracture surface.

Fracture surface depicted in Fig. 5 f shows multiple crack initiation with a smaller and a larger fracture area (marked with arrows) showing typical features of fatigue crack growth, which stands in good correlation with the place of highest temperature measured in Fig. 5 e. A comparison of the temperature evolution with both the change of the nonlinear parameter β_{rel} and the resonance frequency f_R during cyclic loading demonstrates, that the change in temperature is the most suitable/susceptible device as likely indicator for fatigue damage (Fig. 6). Point (1) marked in Fig. 6 indicates the first increase of the temperature T at sample surface corresponding to Fig. 5 a. At point (2) a slight decrease in resonance frequency f_R and nonlinear parameter β_{rel} could be observed. By means of thermography it is possible to quasi in-situ localize the place of crack initiation irregardless of its position at the surface or the interior of the specimen volume. In case of the HAZ EN AW-5083 (Fig. 7 a) the highest temperature evolution was not found in the highest stressed cross section but in the area of the weld seam 8 mm below at a surface pore (Fig. 7 b).

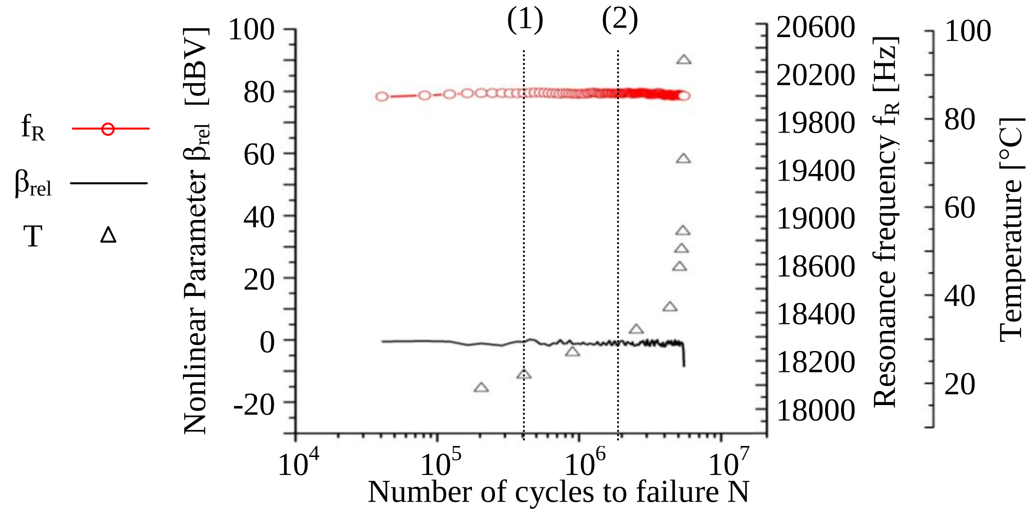

Fig. 6. Resonance frequency (f_R), nonlinear parameter (β_{rel}) and temperature (T) during fatigue test of EN AW-6082, HAZ, $\Delta\sigma/2$ = 70 MPa, $N_f = 5.48 \cdot 10^6$.

Fracture analysis of the sample indicated fatigue failure starting from this pore. Similar failure behavior was observed for all four samples out of HAZ AW-5083. In contrast, all of the samples out of the HAZ AW-6082 failed in the critical cross section, representing the over-aged microstructure of this precipitation-hardening alloy, and not in the near weld seam area.

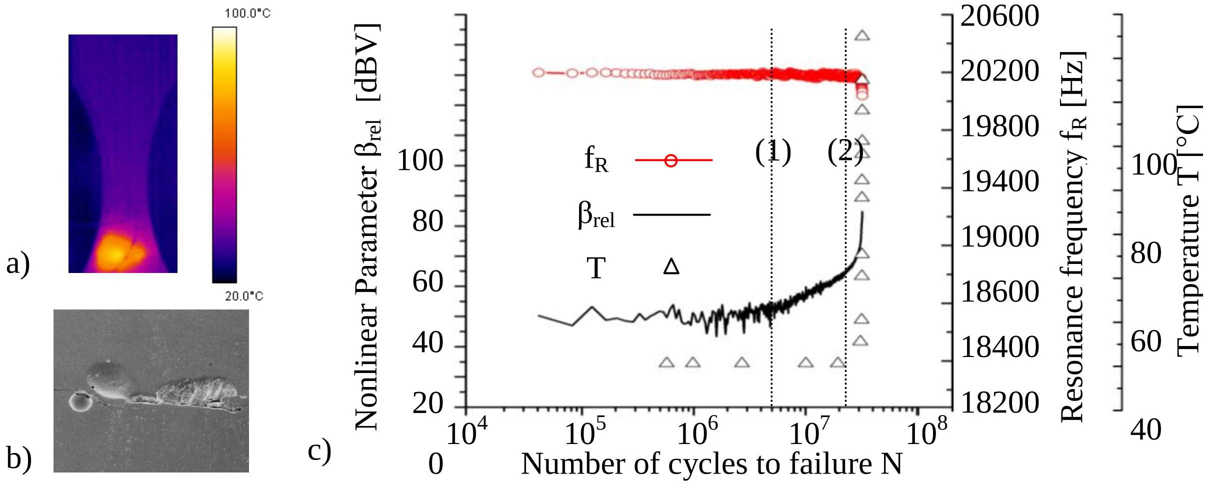

Fig. 7. a) Thermograph of the last pulse at the end of the test of the HAZ out of EN AW-5083 with $\Delta\sigma/2$ = 50 MPa with b) crack initiation side at a surface pore in the area of the weld seam and c) the resonance frequency (f_R) and nonlinear parameter (β_{rel}) and temperature (T).

Both HAZ specimens were tested under the same conditions regarding distance of the critical cross-section to the weld seam area and presence of weld defects. A comparison of the temperature evolution in the specimens representing the two different HAZs revealed a steady temperature increase for the precipitation-hardened AW-6082 (point (1) Fig. 6), while a very sudden temperature increase (detectable only at around 95% of the overall fatigue life marked with point (2) in Fig. 7 c) was observed in the weld seam area for samples out of the work-hardened AW-5083. Hence, fatigue failure in the HAZ AW-6082 is dominated by a steady damage evolution while samples representing the HAZ AW-5083 fail due to sudden and unstable crack growth from defects outside the critical cross section. For the latter constellation thermography is not a suitable technique to follow damage evolution during VHCF loading. Fig. 7 c depicts the course of the nonlinear parameter β_{rel} and the resonance frequency f_R during fatigue testing of the HAZ AW-5083. Point (1) marked in the diagram shows the point of steady increase of β_{rel} and decrease of f_R. Point (2) denotes the number of cycles at which a first increase in temperature could be detected. In this case the increase of temperature was detected later as the change of β_{rel} and f_R. A possible explanation for the earlier damage indication by means of the nonlinear parameter might be the coalescence of microcracks between weld defects (incomplete fusion and pores), being much more reflected in the nonlinear material behavior than in the interacting friction surfaces leading to an increase in sample temperature. However, the difference in stress amplitude and fatigue life for the investigated HAZ samples and its likely influence on the change of β_{rel} and temperature during cyclic loading has to be investigated in more detail. Further investigations are necessary to distinguish between the different physical processes related to the observed discrepancies between the sensitivities towards early damage indication of the techniques presented before a final evaluation of the applicability can be suggested.

Conclusion

Fatigue experiments with welded samples out of the precipitation-hardening Al-alloy EN AW-6082 and the work-hardened EN AW-5083 were carried out by means of an ultrasonic fatigue testing system in combination with the nonlinear ultrasonic technique and an infrared camera. Fatigue life of the weld seam is dominated by shape-edged incomplete fusions in combination with a crack coalescence towards clusters of pores. The change of the nonlinear parameter β_{rel} could be related to the stages of damage evolution at different stress levels. Fracture analysis of fatigued samples representing the weld seam demonstrate the importance of the defect type and position for the VHCF behavior. For samples representing the HAZ AW-6082 a continuous increase in temperature could be observed far earlier than a change in nonlinear parameter β_{rel} or frequency f_R. In contrast, for samples which failed in the weld seam at weld defects such as incomplete fusions and pores only a very sudden change in temperature was observed shortly before failure (at ~ 95% of the overall fatigue life). This phenomenon was typical for samples out of the HAZ AW-5083, where fatal crack initiation started at a distance to the critically loaded cross section. In this case, the nonlinear parameter β_{rel} could be confirmed as indicator with a high sensitivity towards early damage evolution.

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