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Procedia Structural Integrity 24 (2019) 583–592

Structural Integrity Procedia

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AIAS 2019 International Conference on Stress Analysis

Real-time monitoring of damage evolution by nonlinear ultrasonic technique

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Abstract

In this work, the ultrasound technique was used to monitor the damage of material subjected to fatigue loads. Prediction of structural damage is critical for safe and reliable operation of engineered complex systems. In these measurements, conventional ultrasonic probes (transmitter and receiver) were stably fixed to the tested samples with steel brackets, in order to eliminate ever possible variability associated with the coupling of probes. The transmitted and received ultrasonic signals were recorded and analyzed using a digital oscilloscope. The data were converted into the frequency domain using an algorithm developed in Matlab based on Fast Fourier Transform (FFT) for received signal in dependence of the applied stress level and the accumulated fatigue damage was deeply studied in order to recognize quantitative effects, suitable for an experimental prediction of the integrity of the material. The acquired data were compared with the reference signal, at the beginning of the fatigue tests. Particular care has been paid to UT signal attenuation and to the study of the frequency spectrum as the number of load cycles varies. The applied experimental technique has proved efficient for detecting damage induced by mechanical stress.

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Keywords: NDT; fatigue; damage evolution; ultrasonic technique; FFT

1. Introduction

A mechanical element subjected to a high static load in most cases develops a strong plastic deformation before breaking, allowing the component to be replaced beforehand. When, on the other hand, we are dealing with time-varying loads, the component breaks down without warning, in a manner similar to that of a fragile static fracture. Traditionally, the fatigue failure process determined by variable loads is distinguished in three phases. For a well-

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10.1016/j.prostr.2020.02.051

designed component, the first two stages cover 80-90% of its fatigue life (Guo-Shuang et al., (2008)). Over the years, several ND techniques have been proposed to follow the fatigue damage advancement, allowing evaluating the integrity of a component in the absence of alteration of its state. A possibility is the study of the changes that high frequency acoustic waves suffer when a cyclic load is applied. Ultrasonic measurements are a useful tool for estimating the fatigue life of a material because some linear physical parameters (sound speed and signal attenuation) have a high sensitivity to the evolution of the damage (Joshi and Green, (1972); Papadakis, (1976)). However, these parameters do not show enough sensitivity to the accumulation of dislocations and flow lines in the early stages (Szilard, (1942); Nagy, (1998)). Recently, several studies on non-linear acoustics have shown a strong relationship between fatigue damage in the early stages and non-linear effects of ultrasound waves (Cantrell and Yost, (2001); Jhang, (2000); Cantrell, (2006); Barnard, (1999); Abarkane et al., (2017); Norris, (1998)).

In this research an experimental procedure has been proposed for the in situ monitoring of metal specimens using conventional transmitting and receiving ultrasonic probes. The probes were permanently fixed to the specimens using metal supports in order to eliminate any possible variability due to the coupling with the metal surface. The transmitted and received ultrasonic signals were recorded and analyzed using a digital oscilloscope.

The data recorded in the time domain were subsequently converted into the frequency domain using an appropriate analysis algorithm developed in the Matlab environment based on the Fast Fourier Transform (FFT). The comparison of signals measured at initial and different stages of fatigue tests highlighted the existence of temporal variation and attenuation of the fundamental frequency amplitude as the number of load cycles varies. The applied experimental technique proved to be effective in detecting the damage induced by mechanical stress and to predict the fatigue life of metals.

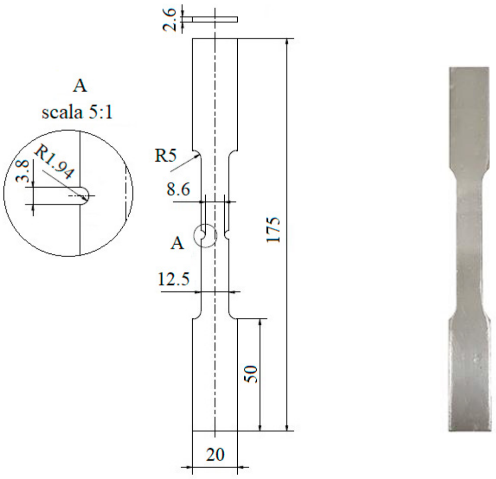
Nomenclature

σ_{max}	maximum stress
σ_{min}	minimum stress
ΔV_{pp}	peak-peak tension
$\Delta V_{pp}/\Delta V_{pp0}$	normalized peak-peak tension
FFT	Fast Fourier Transform
K/K_0	normalized stiffness
PRF	Pulse Repetition Frequency
R	constant stress ratio
v/v_0	normalized UT velocity

1. Materials and experimental procedure

The specimens used for the monitoring of fatigue damage with ultrasonic measurements are made in C45 steel and present a notch in the middle of the gage length (Fig. 1a). A preliminary static test was carried out on a smooth specimen, in displacement control with a velocity of 1 mm/min, according to the ASTM E8-04 standard (Fig. 1b). Table 1 summarizes the data of the static tensile test.

The system employed for in situ measurements during fatigue test includes a portable OmniScan® MX defect unit (Olympus Corporation), an Agilent Technologies DSO-X 2012A digital oscilloscope, two piezoelectric probes GE MWB 45-4, 8x9 and a servo-hydraulic axial testing machine MTS 810-100 kN (Fig. 2a-b). This measurement system allowed recording and analyzing both transmitted and received ultrasonic signals without the need of removing the specimen from the test machine. The probes, with central frequencies of 4 MHz, are used as a transmitter and a receiver respectively, operating in transmission mode. The ultrasonic transducers have been symmetrically positioned with respect to the notched section and aligned optimally with a special tool to optimize and maximize the UT signal. The distance between the two transducers was 41.6 mm and the acoustic path was 58.832 mm for a total of 16 reflections, suitably designed so that the ultrasound longitudinal beam covers the entire area in the region where the notch is present (Fig. 2c). The two pairs of 45° angle beam transducers are coupled with light oil so that the coupling with the surface of the specimen remains stable during the tests.



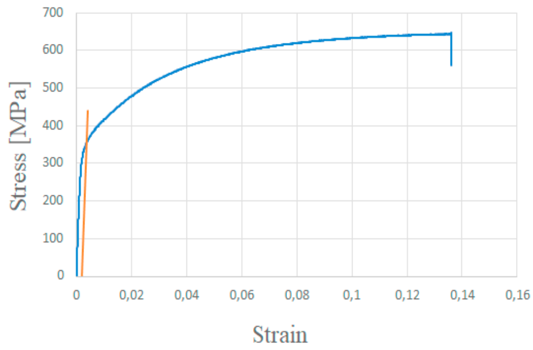


Fig. 1. (a) Notched specimen geometry for UT tests; (b) Stress-strain curve of the un-notched specimens.

Table 1. Experimentally determined mechanical and physical properties

Physical Properties		
Density	7.81	[g/cm^3]
UT Velocity (longitudinal wave)	5503	[m/s]
Mechanical Properties		
Ultimate tensile strength (UTS)	640	[MPa]
Yield stress	350	[MPa]
Modulus of Elasticity	219953	[MPa]
Poisson Ratio	0.29	

Transmitting ultrasonic transducer (TX) was driven by a generator UT OmniScan® MX in order to generate the ultrasonic pulses (500 PRF, 50 V at 4 MHz) and the receiving transducer (RX) was connected to the digital oscilloscope (Fig. 2b).

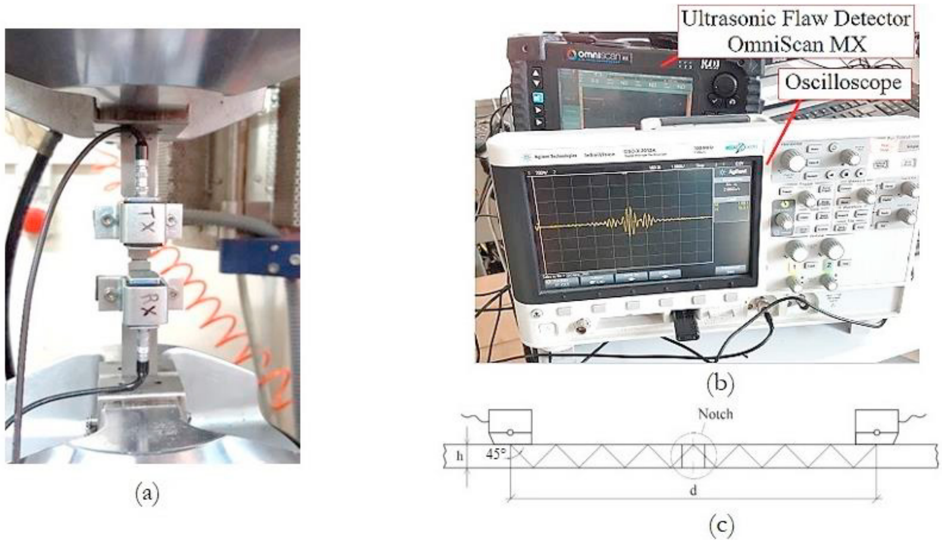


Fig. 2. Experimental setup of fatigue test: (a) specimen loaded onto the MTS 810; (b) UT measurements devices; (c) transducer location on the specimens and UT beam paths (h= 2.6 mm and d= 41.6 mm).

The measurement data have been transferred to a computer for the further processing. In particular, the received signals are recorded with an acquisition frequency of 2 GSa/s by oscilloscope and transferred to a computer for processing in Matlab environment by using FFT to obtain the amplitude of the fundamental frequency. The specimens for the fatigue tests are subjected to tension-tension loading using a sinusoidal waveform at a frequency of 10 Hz. Fatigue tests are performed with R = 0.1. For A1 and A2 specimens the test was carried out with a σ_{max} = 369.8 MPa, while for the specimen A3 σ_{max} = 335.4 MPa. The first ultrasonic measurement was performed on the unloaded specimen and was taken as a reference in order to monitor the progress of the damage. The subsequent measurements were carried out on the unloaded specimen with adequate sampling intervals, depending on the predicted fatigue life.

2. Results and discussion

This section describes the ultrasonic analyses performed on the batch of specimens subjected to fatigue. Several parameters have been selected to monitor the fatigue damage progress and to predict and appropriately evaluate the fatigue life. Among them the attention was focused on the amplitude of the fundamental frequency, peak-peak tension ΔV_{pp}, UT velocity and Time Of Flight. For each specimen some examples of the signal received in-situ were reported during the tests. Moreover, the parameters previously mentioned have been evaluated for the entire fatigue test and plotted against the fatigue life. In the graphs, for each specimen, the instant in which the crack was detected has been highlighted with a specific marker.

In the fatigue test on the A1 specimen, the failure occurred at 45315 cycles. Since ultrasonic measurements were carried out with an interval of 10000 cycles, only limited considerations might be obtained by this test. However, Figures 3a and 3b show the ultrasonic signal received in the time domain before test beginning, which was taken as a reference, and the signal trend over time at 45149 cycles, already in the crack propagation phase, which show relevant signal attenuation. Moreover, the trends of ΔV_{pp} and of the fundamental amplitude as a function of the number of cycles are reported in Figures 4a and 4b. It is possible to observe a similar trend of the two curves that after a constant behaviour, in which ΔV_{pp} is equal to 0.6693 V and the amplitude of the fundamental frequency is equal to 16.74 dB, they decrease first slightly, reaching respectively a value of 0.6513 V and 16.62 dB at 40000 cycles (88% of fatigue life), then rapidly up to a value of 0.3835 V and 14.39 dB respectively at 45149 cycles (99.6% of fatigue life) during crack propagation. Analogous trends could be obtained plotting the UT velocity against the number of cycles (Fig. 4c). Also in this case it was possible to identify in the curve a constant initial region, in which the velocity assumes a value of 5503 m/s. Starting from 40000 cycles (88% of fatigue life), the velocity is lowered, reaching a value of 5487 m/s at 45149 cycles (99.6% of fatigue life). A reciprocal trend is obtained considering the Time Of Flight, which gives substantially the same information of UT velocity.

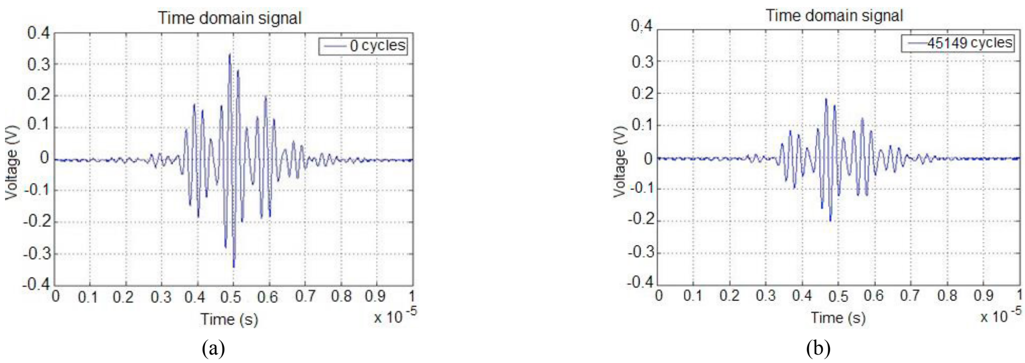
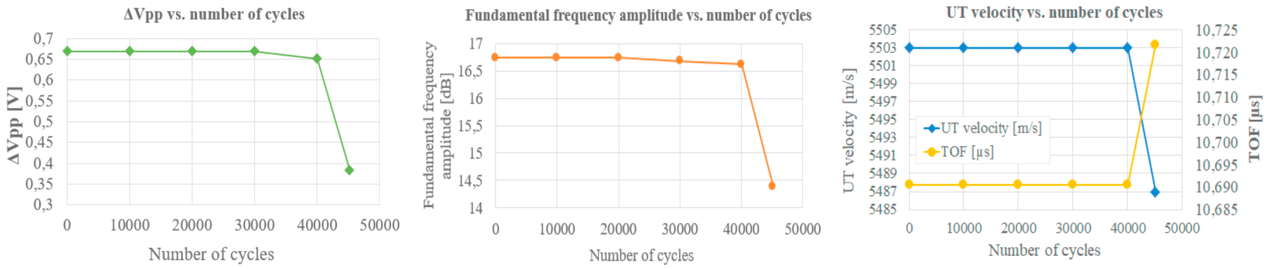


Fig. 3. Example of received time domain signal for the A1 specimen at 0 cycles (a) and at 45149 cycles (b).

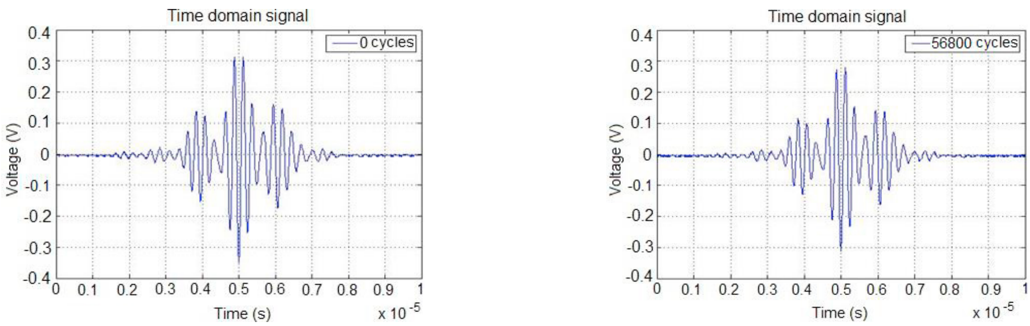
In order to obtain a better description of the phenomenon, the same fatigue test was repeated, adopting a reduced interval between two ultrasonic measurements. In particular, the load step was reduced up to 1000 cycles when approaching the predicted fatigue life. However, A2 specimen showed a visible crack at 58650 cycles (98% of the fatigue life) while the failure occurred at 59580 cycles.



(a) (b) (c)

Fig. 4. Trends of ultrasonic parameters against number of cycles for A1 specimen: (a) Peak-peak tension ΔV_{pp}; (b) fundamental amplitude; (c) UT velocity and Time Of Flight.

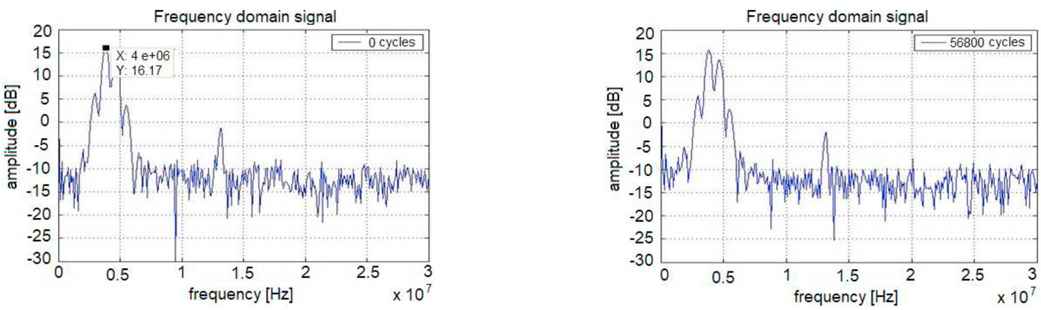
Figure 5a shows the ultrasonic signal received in the time domain before test start, which was taken as a reference for comparing the subsequent UT signals during the whole test. Figure 5b shows the signal trend over time at 56800 cycles (95% of fatigue life), which appears more attenuated than the reference signal corresponding to the beginning of the test. The attenuation could be linked to a change in the physical characteristics of the material, in particular to the more or less marked heterogeneity that disperses the ultrasonic beam in several directions and to the internal micro-damages.



(a) (b)

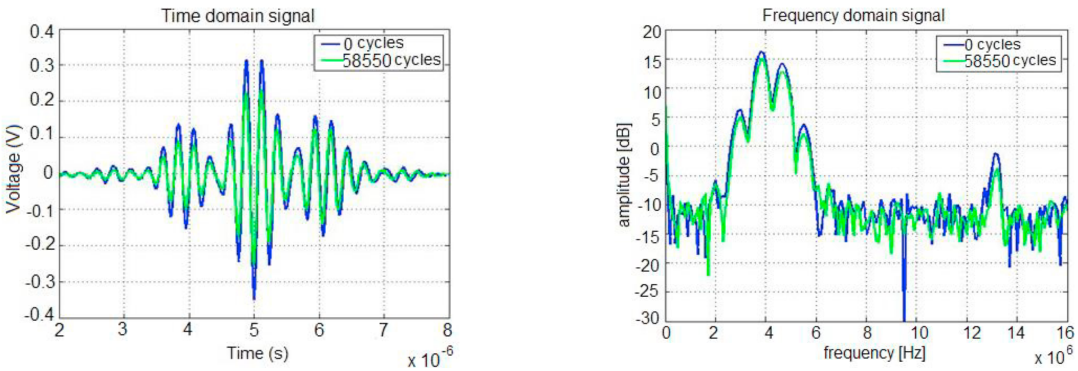
Fig. 5. (a) Example of signal at the beginning fatigue test; (b) Attenuated received signal at 56800 cycles for A2 specimen.

Starting from the time domain data the Fast Fourier Transform (FFT) spectra of the received UT signals is determined and the fundamental amplitude at 4MHz is calculated before test starts (Fig. 6a) and after 56800 cycles (Fig. 6b). An attenuation of the fundamental frequency from 0 cycle reference signal to signal relative to 56800 cycles was observed. In particular, the amplitude was reduced from 16.17 dB to 15.68 dB. A better qualitative evaluation of the changes that the ultrasonic signals suffer after the application of fatigue load cycles can be obtained by the superposition of signals both in time and frequency domain (Fig. 7). These changes are clearly evident at the early stage of crack initiation, before a visible crack is detected.



(a) (b)

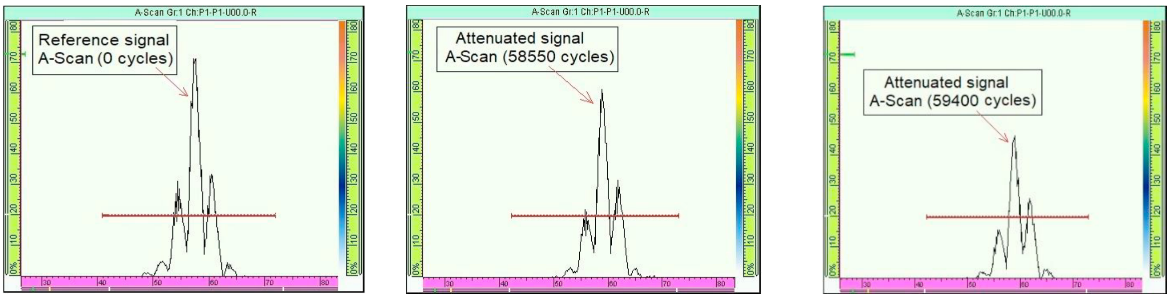
Fig. 6. Example of frequency spectrum (FFT) of the signal at 0 cycles (a) and at 56800 cycles (b) for A2 specimen.



(a) (b)

Fig. 7. Comparison of reference signals for A2 specimen at 0 cycles and at 58550 cycles: (a) time domain, (b) frequency domain.

The attenuation of the reference signal for the specimen A2 at different stages of crack initiation and propagation is clearly highlighted also comparing the UT A-Scan signal (Fig. 8), obtained with a constant gain value of 8 dB. The amplitude at 0 cycle is 70%, reaching 62% at 58850 cycles during the initiation phase and lowering up to 47% at 59400 cycles when a crack is already visible.



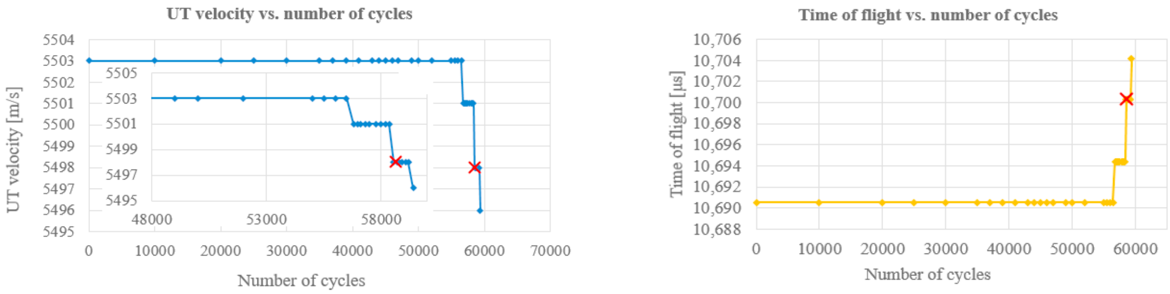
(a) (b) (c)

Fig. 8. Example of A-Scan UT (a) 0 cycles; (b) 58550 cycles and (c) 59400 cycles for A2 specimen.

The changes against the number of cycles of the ultrasound data processed for the A2 specimen are resumed in the following figures. Figure 9 shows the trend of the UT velocity and the reciprocal Time Of Flight as a function of the number of load cycles. Referring for simplicity to the trend of the UT velocity, the ultrasound velocity assumes a constant value of 5503 m/s, up to 56500 cycles, and then starts to decrease with a step trend up to 56800 cycles (95% of fatigue life), where it takes value of 5501 m/s. Subsequently, velocity further decreases (5498 m/s) to 58650 cycles (98% of the fatigue life), instant at which the crack was visible. Then, during the crack propagation phase, it continues to further decrease (5496 m/s) up to the final failure of the specimen at 59580 cycles. This observation is coherent with other data in literature, since the velocity change is sensitive to fatigue-induced micro-damage (Yang et al., (2017)).

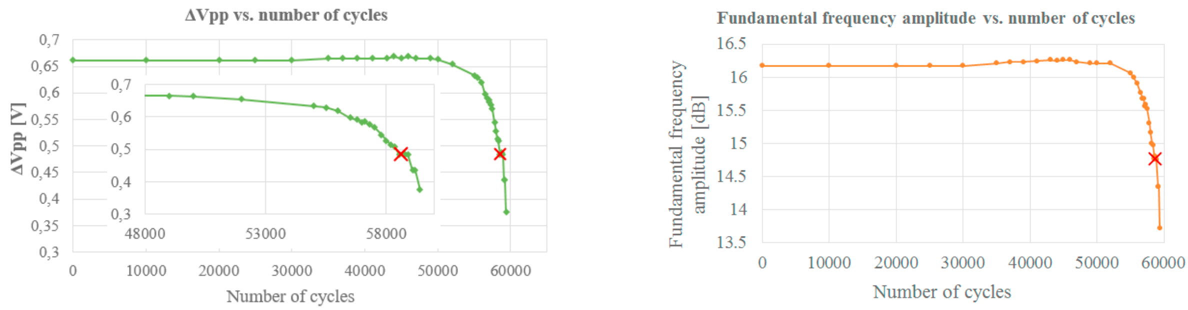
A more interesting behaviour might be obtained considering the trends of the attenuation of the peak-peak tension ΔV_{pp} and of the fundamental frequency with the number of cycles (Fig. 10). These two parameters showed a more regular and continuous behaviour, which is characterized by an increase of their values starting immediately after the half-life of the specimen, followed by a decay that became very fast in the propagation phase. This behaviour is already reported in literature by Green and Pond, (1979), which recognized the sensitivity of attenuation signal measurement to detect early stages of fatigue damage.

A further fatigue test was carried out on A3 specimen, applying a lower load level. In this case, the crack was visible at 130500 cycles (98% of the fatigue life) while final failure was reached at 132650 cycles. Also in this case, the critical examination of the measured signals at different stages confirmed the same behaviour described previously, since a remarkable attenuation of signal at 130000 cycles during initiation phase with respect to the one at the beginning of the test is clearly showed (Fig. 11). For this case, the voltage of the UT transmitted signals was increased from 50 V to 100 V, to analyze its influence on the prediction fatigue. An analogous comparison for A3 specimen of the UT A-Scan signal, using a constant gain of 8 dB allows observing that the attenuation of the reference signal, which assumed initially a value of 70%, is firstly reduced to 54% at 130950 cycle during initiation phase, arriving up to 34% at 131700 during propagation phase (Fig. 12).



(a) (b)

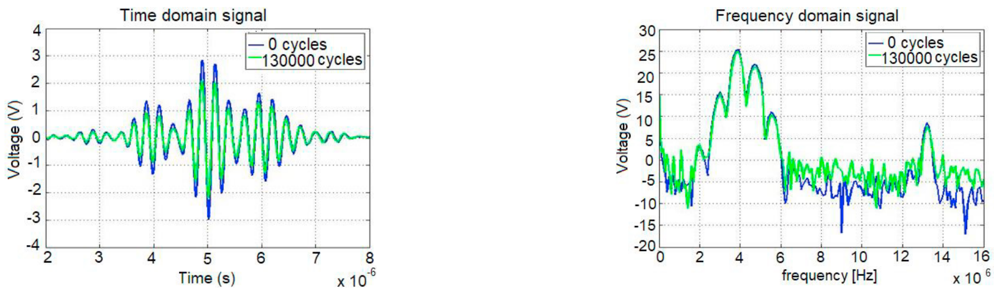
Fig. 9. (a) UT velocity and (b) Time Of Flight trend versus number of cycles for A2 specimen.



(a) (b)

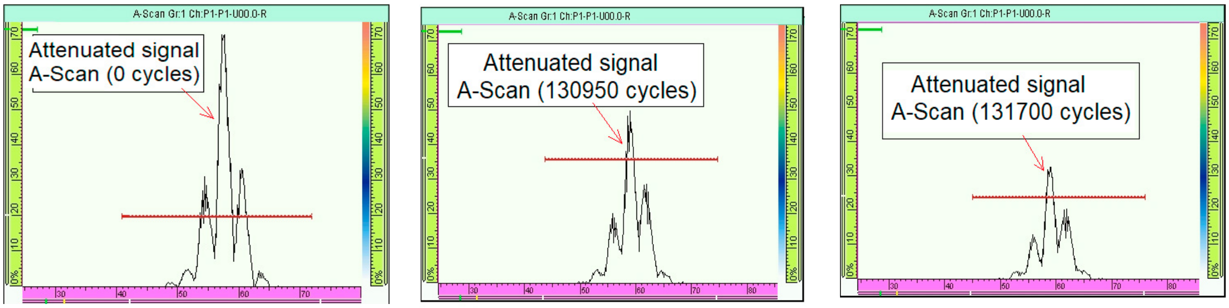
Fig. 10. (a) Peak-peak tension ΔV_{pp} and (b) fundamental amplitude versus number of cycles for A2 specimen.

The examination of the UT velocity and Time Of Flight against fatigue life show a stepped variation at 110000 cycles, which is of difficult interpretation (Fig. 13). In the opinion of authors, this change might not be significant and substantially originated by an error measurement, due to modifications of coupling between probes and specimen surface. The verification of this hypothesis would require a deeper investigation. However, this fact confirms that these parameters are not sufficiently reliable to evaluate the fatigue damage progress. On the contrary, it is important to notice that no trace of this change affects the other two parameters that have been previously selected, ΔV_{pp} and the fundamental frequency. The trends of these parameters for A3 specimen reproduce qualitatively the same behaviour determined at a higher stress level (Fig. 14), suggesting that this behaviour could be effectively determined by the amount of the fatigue damage in the material.



(a) (b)

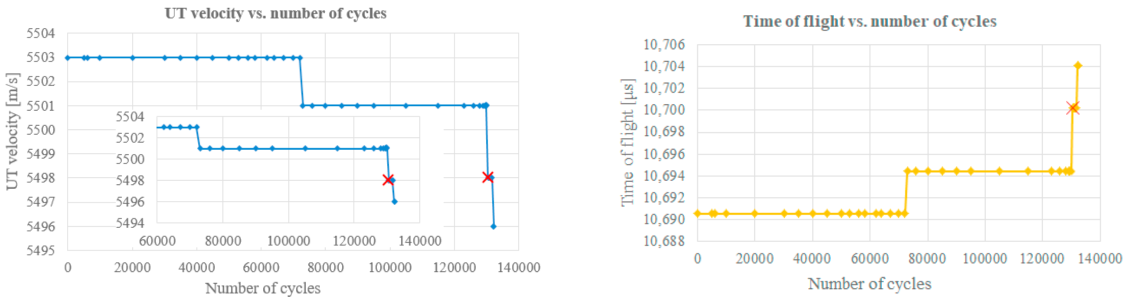
Fig. 11. Comparison of reference signals for A3 specimen at 0 cycles and at 130000 cycles: (a) time domain, (b) frequency domain.



(a) (b) (c)

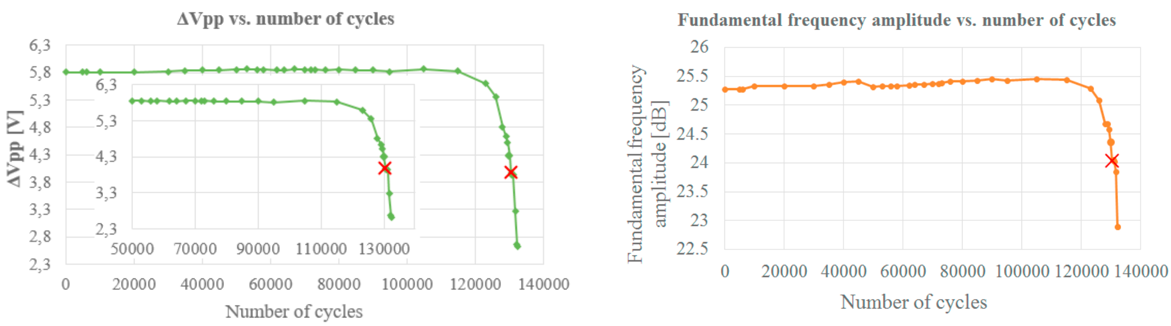
Fig. 12. Example of A-Scan UT (a) 0 cycles; (b) 130950 cycles and (c) 131700 cycles for A3 specimen.

As observed for A1 and A2 specimens, the two curves show a similar trend; after a first almost constant behaviour, where the ΔV_{pp} and the fundamental frequency assume a value of 5.811 V e 25.33 dB respectively, they grow slightly reaching the maximum value of 5.862 V and 25.46 dB respectively at 105000 cycles (79% of the fatigue life) to then decrease starting from 110000 cycles (83% of the fatigue life). Finally, starting from 115000 cycles (87% of the fatigue life) the two curves show a strong and progressive lowering reaching a value respectively of 2.627 V and 22.89 dB at 132000 cycles (99.5 % of the fatigue life) before reaching failure. Once again, a significant variation of the signal was clearly observed before the crack was visible. Moreover, the final decay of the values of these parameters that starts at about 80% of fatigue life is preceded by a continuous and slow increase, occupying a large part of the initiation phase. The results on the A3 specimen confirm that the ΔV_{pp} and the amplitude of the fundamental frequency are more reliable, compared to the UT velocity and TOF, to predict damage and its evolution as for A2 specimen. Even in this case, however, these lasts are not very sensitive for the forecast in the early stages of fatigue life.



(a) (b)

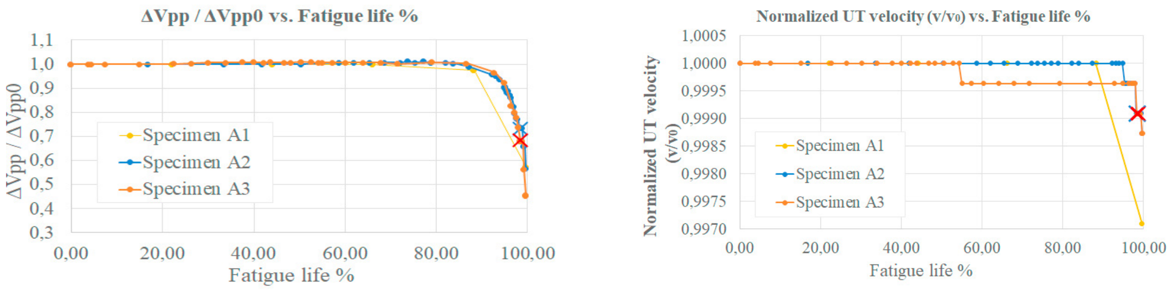
Fig. 13. (a) UT velocity and (b) Time Of Flight trend versus number of cycles for A3 specimen.



(a) (b)

Fig. 14. (a) Receiver signal (ΔV_{pp}) and (b) Fundamental amplitude versus number of cycles for A3 specimen.

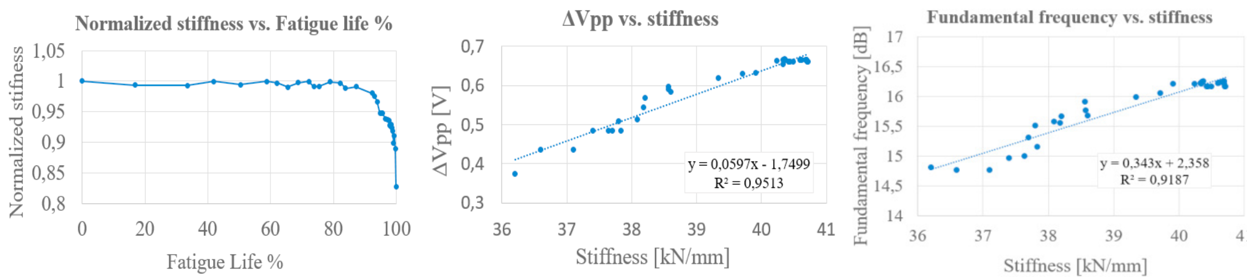
In order to make a comparison between the data collected for the three tested specimens, the signal of each of them was normalized respect to the reference signal relative to the specimen not yet subjected to load cycles ($\Delta V_{pp}/\Delta V_{pp0}$); in the same manner, the number of fatigue cycles was normalized respect to the fatigue life of the specimen (number of fatigue cycles / total fatigue life). In particular, 0% of the fatigue life is therefore referred to the specimen not yet subjected to load cycles while 100% is related to the final breaking of the specimen. Figure 15a shows the trend of the normalized received signal ($\Delta V_{pp}/\Delta V_{pp0}$) as a function of the fatigue life for the specimens A1, A2 and A3. The trend of the three curves is very similar and this result allows to predict the behavior of the material subjected to load cycles, identifying the percentage of life with fatigue reached. In fact, after a constant behaviour, the curves grow slightly reaching a maximum value of around 77-79% of fatigue life and then decreasing starting from about 82-84%, presenting a sharp lowering starting from 86- 87% of fatigue life until failure is reached. Figure 15b shows instead the trend of the normalized speed (v/v_0) as a function of the fatigue life for the specimens A1, A2 and A3. Although the three specimens were derived from the same batch of material, there are still some individual differences in internal microstructure. These intrinsic differences could be the cause of the slightly different course of the three curves. From the graph, it can be seen that if on the one hand the velocity can be used as a qualitative parameter of the progression of damage to fatigue, on the other hand further evaluations are needed on a wider set of specimens to verify that it can also be used as a quantitative evaluation parameter. The UT velocity is in any case less sensitive to the evolution of the damage compared to the variation of the ultrasonic signal ΔV_{pp} and the amplitude variation of the fundamental frequency.



(a) (b)

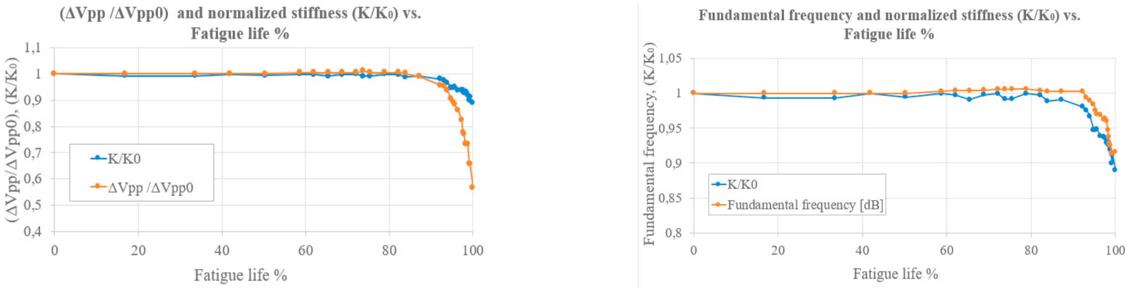
Fig. 15. (a) Normalized UT signal ($\Delta V_{pp}/\Delta V_{pp0}$) and (b) normalized UT velocity (v/v_0) against fatigue life.

By processing fatigue data, the stiffness for the A2 specimen was determined as load cycle varied. Figure 16a shows the trend of normalized stiffness with respect to its initial value as a function of the percentage of fatigue life. The curve shows a trend very similar to that of ΔV_{pp}, presenting an almost constant first part and a slight decrease to 82% of fatigue life. Subsequently, starting from 87% of fatigue life, it decreases rapidly until the specimen failure. Plotting the ΔV_{pp} as a function of stiffness (Fig. 16b), a quite linear relationship was observed between the two variables. As a consequence, the received ultrasonic signal, normalized with respect to the reference signal, and the normalized stiffness, have a very similar trend with the number of cycles. In particular, $\Delta V_{pp}/\Delta V_{pp0}$ begins to progressively decrease starting from 50000 cycles (84% of fatigue life), while the stiffness decreases to 52000 cycles (87% of fatigue life), first very slowly up to 55000 cycles (92% of fatigue life) and than rapidly but more gradually respect to the stiffness, until the final specimen failure.



(a) (b) (c)

Fig. 16. (a) Stiffness against fatigue life; (b) correlation of ΔV_{pp} /stiffness; (c) correlation of fundamental frequency/stiffness for A2 specimen.



(a) (b)

Fig. 17. (a) Normalized UT signal $\Delta V_{pp}/V_{pp0}$ and normalized stiffness against fatigue life; (b) Normalized fundamental frequency and normalized stiffness against fatigue life % for A2 specimen.

However, the comparison reported in Figure 17a allows observing that the attenuation of the signal is much more marked respect to stiffness decrease of the material and therefore, although there is a linear correlation between the two quantities, the UT measurements are a much more sensitive instrument for monitoring the damage failure. The possibility to recognize the beginning of the final failure is less marked if the same comparison is carried out considering the attenuation of the fundamental frequency (Fig. 17b).

3. Conclusions

In the present work, an in-situ ultrasonic method has been developed to monitor and to predict the damage during the fatigue tests. The acquired ultrasonic measurement was compared with the reference signal, at the beginning of the fatigue tests. Particular care has been paid to signal attenuation and to the study of signal spectrum (FFT), in particular the fundamental frequency at different number of cycles. From the ultrasonic measurement performed on the batch of three tested specimens, it is showed that the attenuation of the received signal ΔV_{pp} and the fundamental frequency are more sensitive with respect to UT velocity and Time Of Flight. The trend of curves was very similar for all tested specimens. These trends are similar to the stiffness decay, since a linear relationship between the two quantities has been highlighted. On the other hand, the $\Delta V_{pp}/\Delta V_{pp0}$ parameter has been found to be more sensitive than fundamental frequency and stiffness decay in order to evaluate fatigue damage progress. As a result, with reference to the parameters studied in this paper, the variation of the acoustic response of the ultrasonic wave is very useful for predicting fatigue damage.

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