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Some Results of Ultrasonic Detection of Uniform Corrosion in thin Al2024-T3 Sheets

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Abstract. The ultrasonic detection of uniform corrosion in a thin sheet of aluminum alloy 2024-T3 was investigated at an early stage of corrosion damage. The artificial corrosion, similar to the corrosion in lap joints during operational service, was achieved using a corrosive solution as described in the literature. The corrosion damage intended was relatively weak when it has not yet caused significant changes of thickness and fatigue strength. On the other hand, it has caused significant changes of the intensity of transmitted ultrasonic waves. Maybe this effect can be related to the influence of corrosion damage on the attenuation of waves at the surface layer. The main results of the research shows that even small corrosion damage can be reliably detected by the integrated system (structural health monitoring) at an early stage of its development.

Keywords: Structural health monitoring, uniform corrosion, aluminum alloy, ultrasonic detection

1. Introduction

Structural health monitoring (SHM) of an aircraft should provide reliable detection of any types of the damages dangerous to structural strength. For aircrafts with structural components consisting of aluminum alloy, the most dangerous damages are fatigue cracks which can cause a large decrease in strength of the primary structural components. Corrosion is another type of damage which is widespread in aircraft structures. Existing means of protection against corrosion do not allow completely to exclude corrosion damages. It is known [1], that corrosion is an electrochemical process leading to different types of corrosion which depend the type of metals or alloys, environmental conditions, and the kind and intensity of mechanical loadings.

The most common type of corrosion damage found on aircraft is concentration cell corrosion, or crevice corrosion. Usually it occurs in crevices (shielded areas) such as those formed under gaskets, washers, insulation material, fastener heads, surface deposits, disbonded coatings, threads, lap joints and clamps. It occurs whenever water is trapped between two surfaces, such as under loose paint, within a delaminated bond-line, or in an unsealed joint. Crevice corrosion damage in the lap joints of aircraft skins has become one of the most important problems of a safety after two incidents with Boeing 737 aircraft [3-5]. Analyses of both incidents revealed multiple fatigue cracks that were detected in the remaining aircraft structure, in the holes of the upper row of rivets in several fuselage skin lap joints and to corrosion accelerated fatigue of the fuselage skin panels as the failure mechanism [4, 5]. Another example of crevice corrosion damage was observed at the maintenance of CP-140 Aurora aircraft. Inspection revealed crevice corrosion in the bonded area of the skin plates caused by water penetrating.

In all of these cases corrosion influences the growth of fatigue cracks, but the main effect is connected with accelerating influence of corrosion to the occurrence of a fatigue crack. The initial corrosion damages, causing a crack, as a rule, have the sizes.

Detecting of small damages is a specific and complex problem. Detecting of corrosion-fatigue cracks at stage of their growth is practically the same as well as for fatigue cracks. The accelerating effect of corrosion matters mainly for a correct prediction of remaining lifetime of a structural element.
For the establishment of a structural health monitoring system of an aircraft, uniform corrosion (Figure 1) has a special place. It is one of the most widespread kinds of corrosion. In view of materials wasted, this is the most important form of corrosion. Uniform corrosion is characterized by corrosive attack proceeding evenly over the entire surface area, or a large fraction of the total area. Usually it is believed that general

Figure 1. The surface profile of a detail at uniform corrosion [6]

thinning takes place until failure occurs. Uniform corrosion can be relatively easy measured and predicted, making disastrous failures relatively rare. But also in these cases, occurrence of corrosion means accelerates the ageing of aircraft and demands repair or replacement of the damaged structural components. Therefore, the uniform corrosion must be detected as early as possible. The problem of aircraft corrosion has caused new research and development for protection of a structure against corrosion and its non-destructive inspection. There are already systems of automatic detecting of corrosion damages. The corrosion sensors installed on the CP-140 Aurora were of the electrical resistance type [5]. The loss in thickness of the sensor element due to corrosion processes is directly proportional to the increase in electrical resistance. Eddy current NDT methods are commonly applied also to aircraft during maintenance checks in order to identify the formation of cracks, corrosion, or degradation of rivets [7-10]. With structural health monitoring (SHM) NDT takes a further step, i.e. it is a process of periodically or continuously monitoring and assessing the performance and safety of a structural system based on data obtained from a sensing system integrated into the structure. Here a method of integrating an eddy current sensing system into the structure such that the structure can be remotely monitored in an automated way was developed [11].
The present paper is dedicated to some problems of uniform corrosion detected in a thin

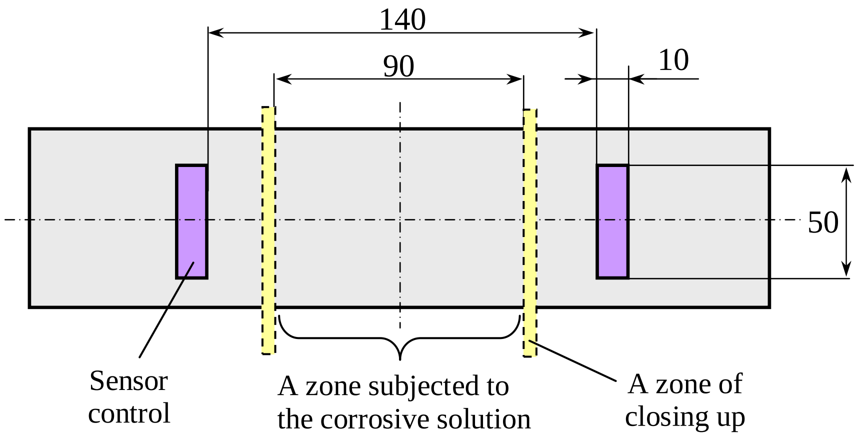


Figure 2. A relative positioning of sensor controls and a zone subject to corrosion between them

sheet of aluminum alloy 2024-T3 by ultrasonic Lamb waves.

2. Experimental Investigation of Uniform Corrosion Ultrasonic Detection

2.1. Material, Samples, Equipment

Well-known aluminum alloy Alclad 2024-T3 was used for the experiment. Different kinds of samples were tested, having a uniform size of 1x80x300 mm (Figure 2). The middle part of the sample was subjected to a corrosive solution.

A rectangular box with nine splits was developed. The distances between splits were 18-20 mm. After the assembly of the box all joints were hermetic covered. The box with samples is shown in Figure 3. For stirring the solution the block which includes a power unit and system of a drive in this case was used?? The device for stirring the solution consists of a little motor (2100 rev/min, 9 V, power 1.1 W). Belt drive decreases angular velocity of a mixing blade about in 4 times.

Electronics LWDS45 of Cedrat Technologies with controlling software developed at the Katholike Universiteit Leuven (K.U. Leuven) was used for the excitation of ultrasonic signals. A 5-cycle sine burst signal at 250 kHz was used to excite the actuators at their approximate resonance frequencies. The time window of a burst was 20 μcs, and the amplitude did not exceed 1.5 V. The Lamb waves excited by the actuators propagated along the plate and were received by the sensor. The response was amplified and transferred to a digital oscilloscope PXI-5105 (National Instrument**)**. Cypher Instruments Ltd equipment C60 was used for impedance measurement to check sensor performance at different stages of the experiment.

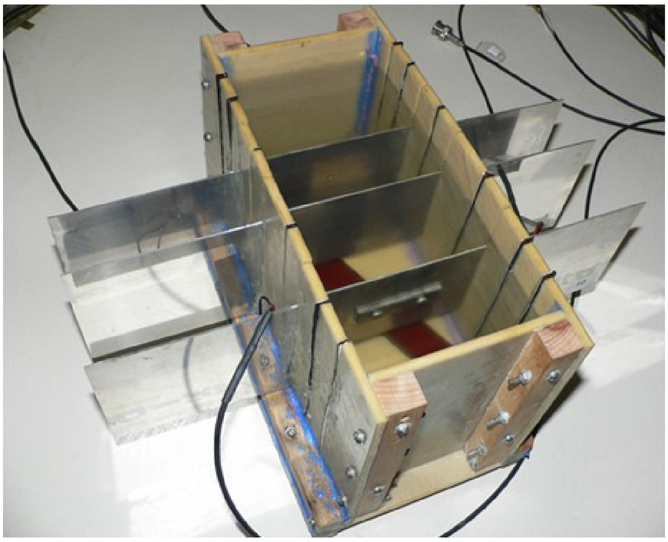


Figure 3. A general view a box with three inserted samples for corrosion test

2.2. Structure of a Solution

The approach of modeling corrosion damage developed in [12] has been chosen as a basis of accelerated corrosion of the testing samples. The authors describe a method for obtaining a solution that develops corrosion damage comparable to corrosion within the lap joints during service. The solution obtained was analyzed chemically and these results were used to develop a dedicated testing solution. It was shown that the corrosion topography that developed with exposure to this solution was similar to samples that had corroded in the field. The most common corrosion topography observed within lap joints obtained from the field was general corrosion. This approach corresponds to the requirements of ultrasonic detection of uniform corrosion. Therefore, as recommended in [12] the testing solution contains 20 mM sodium chloride (NaCl), 4 mM sodium bicarbonate ($NaHCO_3$), 4 mM sodium nitrite ($NaNO_2$), and 2 mM sodium fluoride (NaF) at pH 9 has been chosen for modeling of corrosion damages.

2.3. Initial Fatigue Crack and Corrosion Test

The sample used here has a central hole with a diameter of 4 mm. Before corrosion attack this sample was subjected by alternative loading with maximum 12 kN and a cycle ratio 0.333. Maximum stress in the nominal section was 150 MPa and frequency of alternative load was 20 Hz.

As a result of this stage of testing the initial crack 0.6mm has appeared after 132300 cycles.

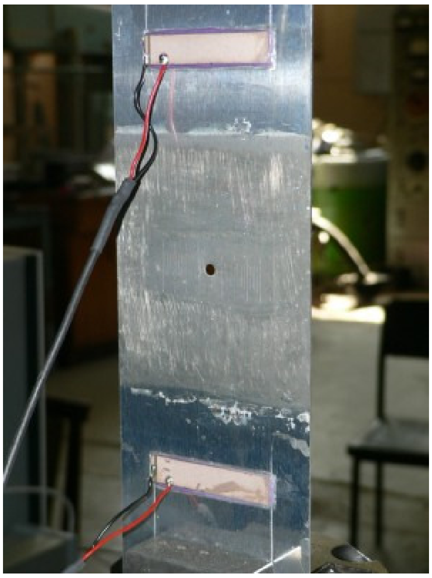


Figure 4. The sample with sensors and corrosion damage

The central part of a sample (width of 80 mm - see Figure 4) was exposed to the corrosion test. The central part from both sides of a sample was initially cleaned by acetone. One side of each sample was processed (scratched) by emery paper, and cleaned again. Corrosion tests were performed over a period of about 4 weeks. The mixer was operating in daytime, and the solution was three times replaced.

Figure 4 shows the sample with the corroded surface. It can be seen that the texture of the corroded part of surface is significantly changed.

More detailed investigation shows:

1) There was no measurable decrease of thickness i.e. no significant loss of material occurred.
2) The corrosion topography observed on the surface of the sample is general corrosion and similar to that obtained in the literature [12].

2.4. Fatigue Test

After corrosive attack, the sample was subjected to cyclic loading. The assessment of the effect of corrosion damage on the fatigue strength was the main goal of this investigation. The growth of the fatigue crack is well described by Paris' law with an exponent 2.5 and a constant $5.3 \cdot 10^{-7}$, if the crack rate is measured in mm/cycle, and stress intensity factor is given in MPa $\cdot m^{0.5}$. The comparison of the growth rate of this corroded sample and the non-corroded reference shows that the effect of the given corrosion damage on the fatigue strength is not significant.

2.5. Non-destructive Detection of Corrosion Damage

The records of response of the sample using ultrasonic non-destructive testing before environmental degradation and with corrosion damage are presented on Fig. 5 and 6. In both cases the total signal can be considered as sequence of impulses, each of which has the general properties with an impulse of excitation (the basic frequency, envelope line of a function, number of cycles) with distortions which are defined by the interaction of closely located impulses. It is possible to note that the signal changes for a sample with corrosion damage. It is obvious, that the first impulse of the response defines the direct wave received by a sensor. It is visible, that the intensity of a direct wave after corrosion damage has decreased. Other impulses correspond to the reflected waves from edges of the sample. The intensity of the reflected impulses also changes, but differently in each interval of time.

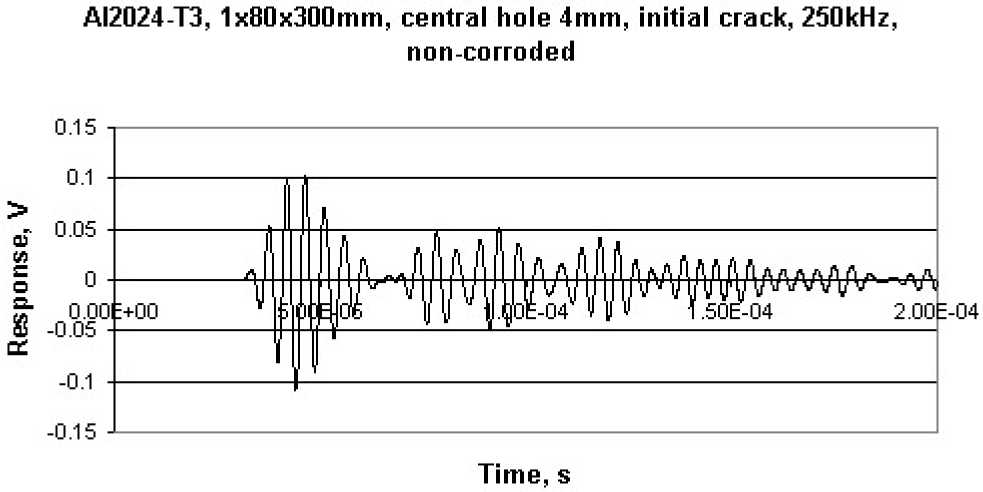


Figure 5. The record of response at the ultrasonic non-destructive testing of the sample before environmental degradation

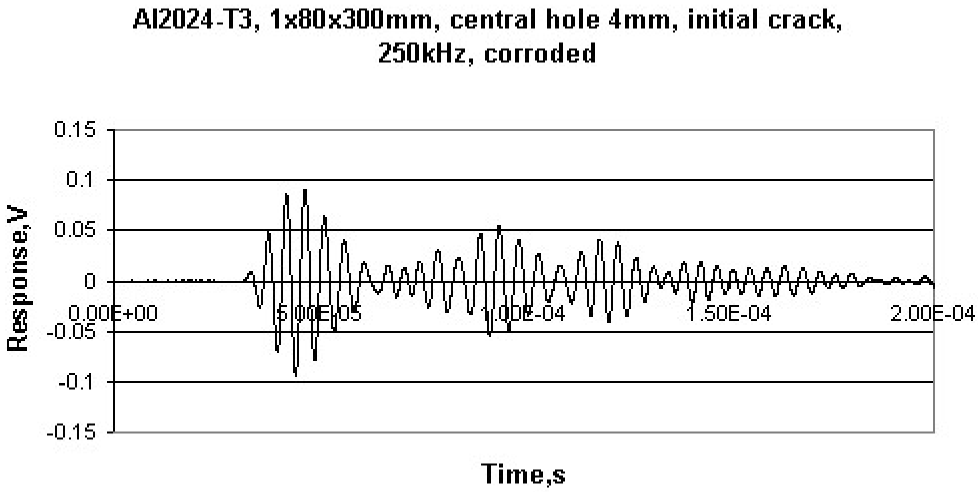


Figure 6. The record of response at the ultrasonic non-destructive testing of the sample with corrosion damage

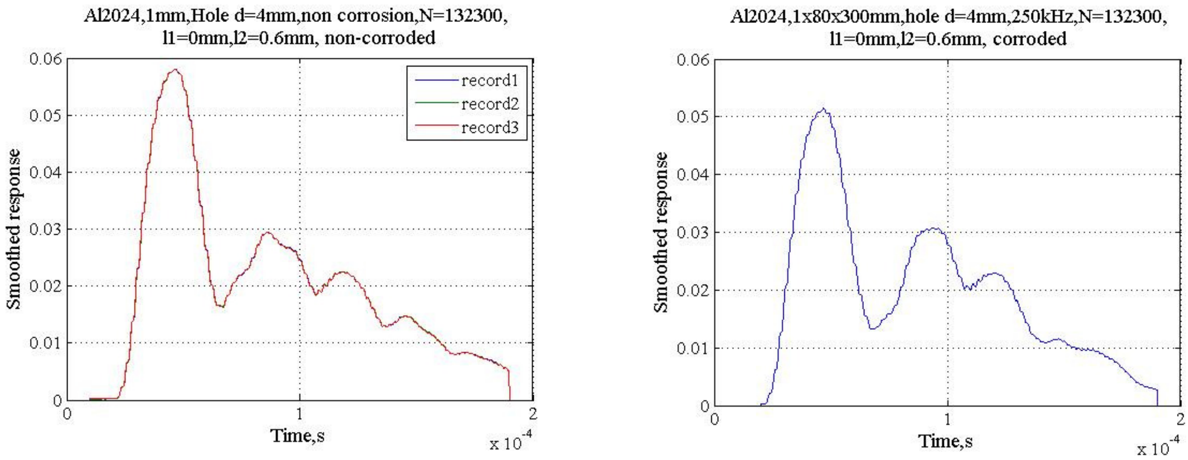
2.6. Signal Processing for Damage Detection

The function of a response was transformed for obtaining steadier parameters of its intensity. There are a number of simple time domain measures in structural damage detection [7]. These include response maximum and minimum and peak-to-peak of a response (a difference between the maximum and minimum), arrival time - absolute time when the signal first crosses the threshold level and others simple parameters of a response. The Root Mean Square (RMS), statistical moments are more complex parameters of signal.

With purpose to enhance damage identification a sensor signal was smoothed. There are many low-pass filters for data smoothing [7]. The function

$$S(t)=\sqrt{\frac{\sum_{i=n-\Delta n}^{n+\Delta n}(s_i-\bar{s})^2}{2\Delta n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

is used here, where Δn is number of samples in time interval Δt. This interval was established to obtain the smoothness of a functions ***S(t)*** that indicates differentiability of this function. The maximum value S_{max} of the function ***S(t)*** was used as main feature of signal for a damage identification.



a) *b)*

Figure 7. Smoothing function for the responses shown in figure 8 (a) and 9 (b).

2.7. Main Result of Analysis

Figure 7 presents the result of smoothing of responses for the non-corroded and the corroded state. Three records of smoothed response are presented for the non-corroded state of a sample. It can be seen that the smoothing functions for all records are practically the same. There is a similar result for the corroded state of the sample too. This gives important evidence of the high reproducibility of ultrasonic measurements. Figure 8 presents a diagram of the maximums of smoothed responses.

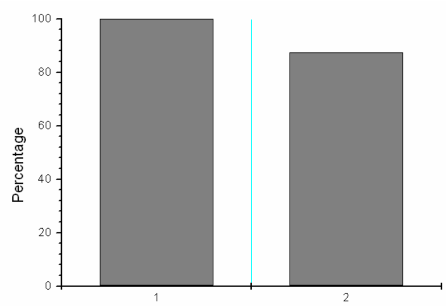


Figure 8. Comparison the maximum intensity of response at non-corroded (1) and corroded (2) states of a sample

It was noted above, that during the second stage of the experiment the sample with the corrosion damage was subjected to cyclic loading. The process of loading was interrupted and the same ultrasonic non-destructive test was performed when the crack was grown approximately in steps of 2mm. Results are presented in Figure 9. Initial parameter S_{max} for non-corroded state of a sample is presented by a cirlce. Points 1 represent values in initial corroded state These results are compared with analogous measurements of another non-corroded sample (the points 2).

It is seen both samples in initial non-corroded state have practically the same values of parameter S_{max}.

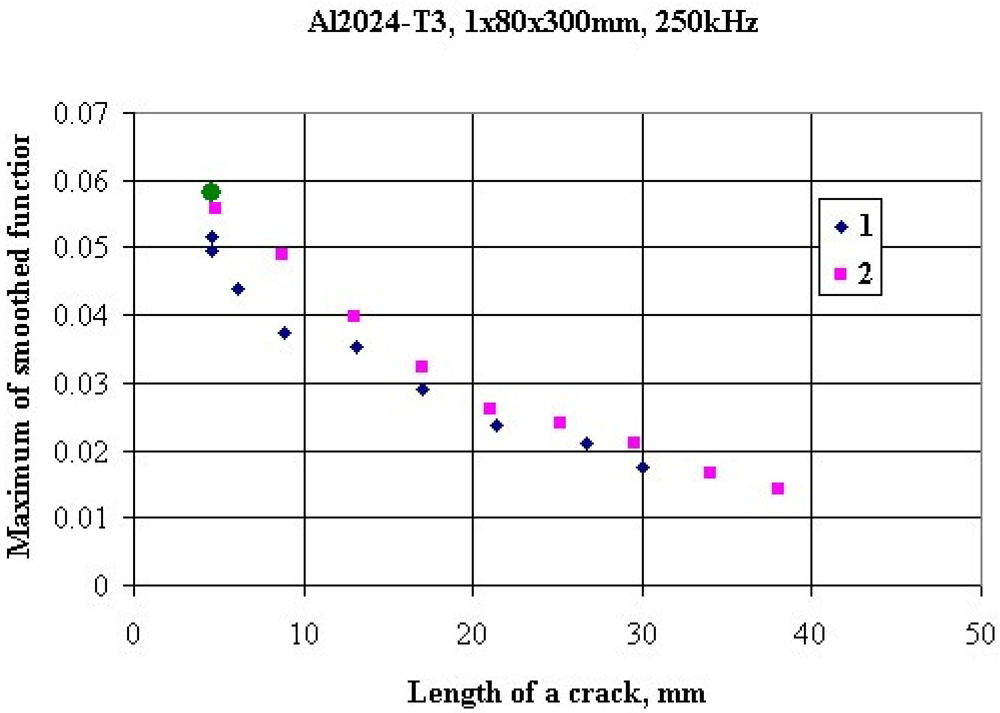


Figure 10. Response as a function of crack length: 1 – the sample with corrosion, 2- non-corroded sample

3. Conclusions

In the given research, general corrosion damage is applied by an artificial corrosion process. This progress of this damage was stopped when it has not yet caused some significant change of material thickness or fatigue strength. At the same time, this damage has caused significant change of intensity of ultrasonic waves (Figure 10 and 11). In the given experiment the maximum of the smoothed response in corroded sample has decreased for 12.8 % in comparison with non-corroded one. The effect of corrosion remains also at the subsequent growth of a fatigue crack. On Figure 12 it is clearly visible, that intensity of an ultrasonic signal of corroded sample remains smaller during growth of a fatigue crack, at least, within the length of 20-25 mm. The obtained result is a little bit unexpected. The comprehensible preliminary explanation of this effect can be related with influence of corrosion damage of a surface on intensity of attenuation of waves in a surface layer. However, additional experiments and the analysis are required.

Anyway, it is possible to conclude definitely that surface corrosion damage of even small intensity can be reliably detected by the integrated system of structural health monitoring at an early stage of its development. Another important conclusion is that the growth of a fatigue crack in a zone with corrosion damage can be identified as a little bit increased due to corrosion damage. This opens prospects of creation of some generalized model of remaining strength and remaining lifetime at monitoring corrosion -fatigue damages.

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