Nodestructive microwaves methods for detection of micro-cracks on stainless steels

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Abstract – The aim of this study is the presentation of a new non-destructive testing technique on stainless steels by the near field using microwave devices. This technique will allow the detection of micro-cracks in the surface of stainless steels. We will be using for this purpose a microstrip antenna characterized by a resonance frequency of 8 GHz. The simulation software High Frequency Structure Simulator (HFSS) will be used for the calculation of the variation in the resonance frequency and reflection coefficient that caused by the defect. This defect is assimilated to a rectangular groove. The obtained results are very interesting because we arrived to detect a crack depth less than 20 µm. Furthermore, industrial ultrasonic testing methods do not always detect satisfactorily defects of small depth (less than 5 mm) located near the inspection surface.

Keywords: Stainless steel, micro-crack, microwave, reflection coefficient, resonant frequency.

1. Introduction

Nuclear central, like all industrial installations are subject to aging that can affect the safety of the installation: aging of structures (buildings, circuits, metal components) and process control elements (control systems, actuators ...). In view of the experience feedback this notion of aging, linked to the age of the installation is extended to unexpected degradation, regardless of the time of onset. A Master of aging element consists of the possibilities of repair, replacement or modification of the affected elements [2].

Some components may be non-replaceable or difficult to repair. In this case, the aging of these components conditions the lifetime of the installation. For such equipment, the steps taken in the design and monitoring provisions are essential. Investigations of understanding cracking phenomena have shown the need to review the endurance limit used for austenitic steels.

The early detection of surface defaults by Non Destructive Testing (NDT) allows relevant preventive maintenance of installations avoiding as far as is possible from having to disassemble, repair or replace prematurely service components [3]. Our study is part of this framework. We are interested in the detection of cracks on the surface of stainless steels. Currently, the majority of automated non-destructive testing solutions are based on techniques using ultrasound [4] or eddy currents [5]. However, in spite of their high sensitivity and resolution, these methods are not necessarily adapted for all situations encountered in practice. Therefore, different research is underway to improve the detection of the dimensioning and modelling of surface cracks in conductive materials. Furthermore, industrial ultrasonic testing methods do not always detect satisfactorily defects of small depth (less than 5 mm) located near the inspection surface [1]. To overcome these limitations, it seemed interesting to assess the potential of microwave techniques to detect surface micro-cracks in metals, in addition to studies of more traditional control methods.

The first technique in the near field consists in measuring changes in the reflection parameter induced by a defect localized near of the opening of an open propagation structure as rectangular waveguide [6], [7] or coaxial line [8]. Default dimensions are then deducted from the changes observed in the amplitude and phase of the reflection coefficient, prior calibration performed by placing the sensor in front of a faultless material. In addition, the use of waveguides terminated by a slot antenna [9] or by a taper or by a dielectric waveguide [10], has helped to improve the spatial resolution and sensitivity of detection. These methods have been successfully applied to detect surface cracks [6], [8]. In [11], a simulation study concerns the detection of cracks in the pure iron based on the use of microwaves and resonant microstrip circuits.

The remainder of the paper is organized as follows. A structure under test for the characterization of defects is described in section 2. The simulation results of micro-cracks detection simulation in stainless steels are presented in the section 3. Finally, to conclude, remarks are given in section 4.

2. Structure under test for the characterization of defects

To characterize the defects on the surface of a stainless steel, a microstrip antenna designed to operate at a frequency of 8 GHz [12] is placed on the upper surface of the material under test. The antenna is maintained at a distance of 1 mm above the sample (Figure 1).

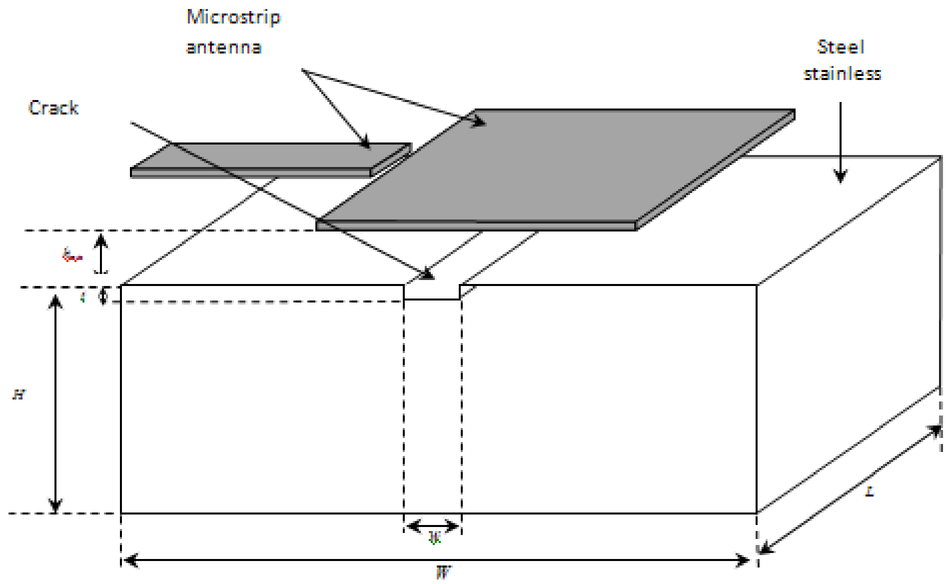

Figure 1: Structure under test for the characterization of defects.

2. 1. Description of the microstrip antenna

The antenna used is studied by Satthamsakul S. et al. [12]. It's a planar rectangular patch antenna fed by microstrip line on the PCB (printed circuit board) FR4 substrate with dielectric constant εr = 4.5, loss tangent tanδ = 0.02 and 1.6 mm of thickness (figure 2). This antenna characterized by a resonance frequency of 8 GHz. The width and length of the patch are 15.8 mm and 8.0 mm respectively. The total size of the antenna with ground plane is (34 × 20) mm2.

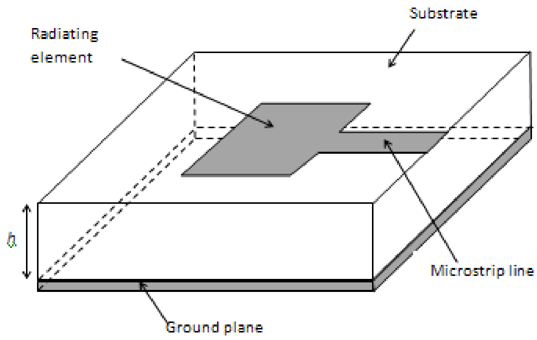

Figure 2 : Géométrie de l'antenne patch.

Figure 3 shows the results found by Satthamsakul S. et al [8], and the HFSS simulation result of a patch antenna [13]. We can conclude that the calculation results are near the point of view of the location of the resonance and those of the amplitude versus the frequency. This remark leads us to validate our results in a limited frequency band around the resonance frequency referred and that our potential applications will be considered.

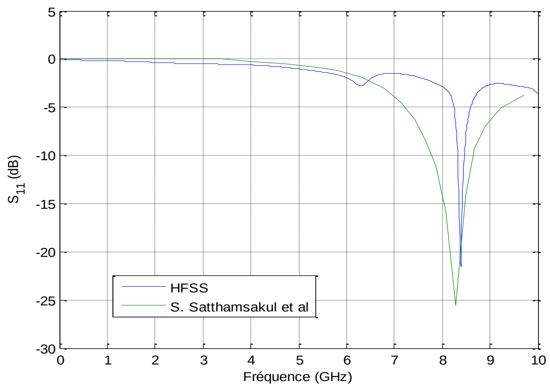

Figure 3: Reflection coefficient |S11| dB measured by S. Satthamsakul and simulated by HFSS.

2. 2. Studied material: stainless steel 304L

Table 1: Chemical composition of the stainless steel 304L in accordance with ASTM A240.

Elément	% en masse
Carbon (C)	0.030 max.
Manganese (Mn)	2.000 max.
Posphore (P)	0.045 max.
Sulfur (S)	0.030 max.
Silicium (Si)	0.750 max.
Chrome (Cr)	18-20
Nickel (Ni)	8-12
Nitrogen (N)	0.100 max.
Iron (Fe)	Mass percentage remaining

In this study, we mainly focus on the detection of surface defects in plates of stainless steel 304L. This material is widely used in industry, particularly in nuclear power. It is present in particular in the pipes of the primary and secondary circuits of nuclear central. The major advantages of stainless steel 304L are excellent corrosion resistance [14]. The table 1 shows the chemical composition of the stainless steel 304L in accordance with ASTM A240 [2]. The table 2 shows the electrical, physical and thermal characteristics of stainless steel 304L [2].

Table 2: Electrical, physical and thermal characteristics of stainless steel 304L.

Electrical conductivity (MS/m)	1.4
Density (g.cm^{-3})	7.93
Melting point (°C)	1400 à 1455
Coefficient of thermal expansion (× 10^{-5} K^{-1})	18 entre 20 et 100°C
Thermal conductivity (W.m^{-1}.K^{-1})	16.3 à 23°C

3. Results and discussions

The simulation results were intended to validate the principle of detection of micro-cracks in stainless steel plates by microwave techniques. It is important at this point to note that changes in the resonant frequency and the amplitude of the reflection coefficient of the microstrip antenna, noted *fr* and $|S_{11}|_{dB}$ respectively, are caused by a crack. Due to this, we used plates in stainless steel 304L with length L equal to 20 mm, width W of 20 mm and height of 5 mm, these plates contain different rectangular nicks which are distinguished by their length *l* (4 6 and 8 mm), width w (1, 1.5 and 2 mm) and their depth t (10, 20 and 30 microns).

Figure 4 shows the variation in frequency and the variation of the reflection coefficient obtained through the simulation in HFSS antenna located above 1 mm of a faultless sample and above a sample having a groove with a length *l* = 4 mm, width w = 1 mm and a depth of t = 20 µm. We can observe a variation of the resonant frequency Δf_r = 25 MHz and a variation of the module of the reflection coefficient $|\Delta S_{11}|_{dB}$ = 3.15 dB, which demonstrates the feasibility of our technique. This result is in good agreement with those proven by the work of researchers [6].

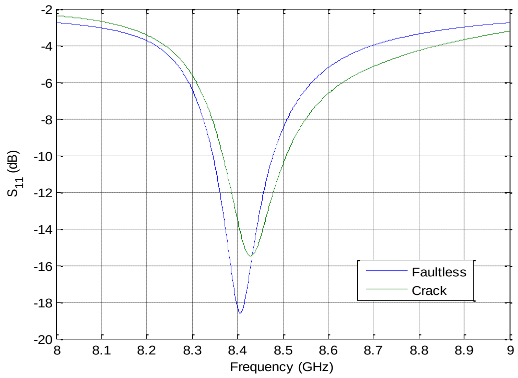

Figure 4: Reflection coefficient of the sensor obtained above a faultless stainless steel and above a stainless steel with a crack.

3. 1. Effect of the length of the crack

The width and depth of the crack are fixed to 1 mm and 10 µm successively. Table 3 shows the variation in the resonance frequency and the variation in the reflection parameter of the sensor above metals (stainless steel) contains cracks of different length.

Table 3: Variation in the reflection coefficient obtained at the simulation with HFSS of the antenna above metals contains different lengths of crack.

Length of the crack (mm)	4	6	8
f_r (MHz)	8415	8526	8692
Δf_r (MHz)	0008	0119	0285
S_{11} (dB)	-27.8453	-15.1597	-6.5762

3. 2. Effect of the width of the crack

The length and depth of the crack are fixed to 4 mm and 10 µm successively. Table 4 shows the variation in the resonance frequency and the variation in the reflection parameter of the sensor above metals contains cracks of different width.

Table 4: Variation in the reflection coefficient obtained at the simulation with HFSS of the antenna above metals contains different widths of crack.

Width of the crack (mm)	1	1.5	2
f_r (MHz)	8415	8423	8520
Δf_r (MHz)	0008	0016	0113
S_{11} (dB)	-27.8453	-18.9975	-8.6623

3. 3. Effect of the depth of the crack

The length and width of the crack are fixed to 4 mm and 1 mm successively. Table 5 shows the variation in the resonance frequency and the variation in the reflection parameter of the sensor above metals contains cracks of different depth.

Table 5: Variation in the reflection coefficient obtained at the simulation with HFSS of the antenna above metals contains different depths of crack.

Depth of the crack (µm)	10	20	30
f_r (MHz)	8415	8429	8487
Δf_r (MHz)	0008	0022	0080
S_{11} (dB)	-27.8453	-15.4965	-10.3427

According to the three previous tables, we can see that: the simulation in HFSS antenna located above a sample with a longest groove, wider groove and deeper groove the resonance frequency (f_r) and its variation (Δf_r) become greater and that the reflection coefficient is smaller. These results are in good agreement with the results obtained in [11], [15].

4. Conclusion

In this study, we presented a non-destructive testing and non-contact technique on metals by the microwave technical. This technique allows the detection of micro-cracks (similar to the grooves) on the surface of stainless steels. We have found that: in the HFSS simulation of the antenna located above a sample with a longest groove, wider groove and deeper groove the resonant frequency (f_r) and its variation (Δf_r) became bigger and the reflection coefficient became smaller.

We have demonstrated by simulation the feasibility of the detection of micro-cracks on stainless steels where we detected a crack depth of 10 µm.

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