USING OF MICROWAVES AT INVESTIGATION OF SOLID MATERIALS INHOMOGENITIES

Dagmar Faktorová

University of Žilina, Faculty of Electrical Engineering, Department of Electromagnetic and
Biomedical Engineering, Žilina, Slovak Republic
faktor@fel.utc.sk

Abstract

The paper describes microwave measurement of metal defects using the relevant theoretical assumptions. The cracks are judged from the point of view microwave practice and waveguide technique and formulae are exploited. Measurement results are plotted in graphs and discussed.

1. Introduction

Non-destructive testing (NDT) as a part of many technologies includes various techniques for detecting undesirable random events accompanying industrial and operating processes. These NDT techniques must be adjusted to individual needs and materials. From this point of view it would be serviceable to dispose of a technique applicable for as much as possible testings and also e.g. NDT application without a conducting transducers to test conductive materials, dielectrics and things like that.

Among most occurring defects belong cracks more particular not only the traditional cracks in metals, but currently, with the developing automobile, aircraft and also ship industry and cracks detection in plastics is becoming important, too. More methods for such defects determination are used and we will mention only some of them. The electromagnetic non-destructive evaluation of metal surfaces can be accomplished using thin – eddy current, AC field measurement, and microwave techniques. Besides using microwaves on plastic NDT, a considerable attention is being given to the microwave NDT of metals. The main competing technologies with microwave NDT are ultrasound, eddy current and thermal imaging. Ultrasonic waves usually require a contacting media. Microwaves also allow the crack detection under various coating [1] without the need for coating removal prior to testing. Microwave can potentially generate higher resolution images with deeper penetration then the thermal and eddy current techniques [2]. More microwave techniques can be used for verifying their suitability for this purpose.

Having considered these circumstances also with regards to the extensive area of using microwaves (e.g. [3] gives 25 investigations by means of microwaves) we decided on the basis of theoretical assumption to take heed of using microwaves for these purposes.

2. Theoretical basis and applied formulae

As to general approach to the problems, Maxwell equations provide the basis to solution and for the experimental part we have chosen the waveguide technique making use of the same theoretical basis.

Every component of electromagnetic field satisfies the some equation with three coordinates and for the transversal electric field **E** having a sinusoidal character with the angular frequency ω we can write

$$\frac{\partial^2 \dot{\mathbf{E}}}{\partial x^2}+\frac{\partial^2 \dot{\mathbf{E}}}{\partial y^2}+\frac{\partial^2 \dot{\mathbf{E}}}{\partial z^2}+\frac{\omega^2}{c^2}\dot{\mathbf{E}}=0\,, \qquad (1)$$

where $\frac{\omega}{c}=\frac{2\pi}{\lambda}$ is the phase constant for the TEM waves and λ is the wavelength in free space. On the assumption that the change of the **E** in dependence on coordinate *x* has the form

$$\frac{\partial^2 \dot{\mathbf{E}}}{\partial x^2}=-\beta^2\dot{\mathbf{E}}\,, \qquad (2)$$

where $\beta = \frac{2\pi}{\lambda_g}$ is the propagation constant and λ_g is the wavelength in the waveguide, we get

$$\frac{\partial^2 \dot{\mathbf{E}}}{\partial y^2} + \frac{\partial^2 \dot{\mathbf{E}}}{\partial z^2} + \left(\frac{\omega^2}{c^2} - \beta^2 \right) \dot{\mathbf{E}} = 0 . \qquad (3)$$

From the condition for **E** on the waveguide surfaces it can be shown that

$$\lambda_g = \frac{\lambda}{\sqrt{1 - \left(\frac{\lambda}{\lambda_c} \right)^2}} , \qquad (4)$$

where λ_c is the cut-off wavelength.

We will give still some formulae we used for the evaluation of the measured quantities. For the impedance $\dot{Z}$ which characterizes the conditions in waveguide is applied

$$\dot{Z} = \frac{\dot{E}}{\dot{H}} . \qquad (5)$$

In our experiment we use TE waves and therefore we give the representation only for these ones. For the characteristic impedance of the waveguide we get

$$\dot{Z}_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \frac{1}{\sqrt{1 - \left(\frac{\lambda}{\lambda_c} \right)^2}} , \qquad (6)$$

where $\sqrt{\frac{\mu_0}{\varepsilon_0}}$ is the characteristic impedance of the free space.

As our experiments are based on the reflected signal from defects our measurements and calculations are based on this reality exploiting the waveguide technique, where the reflection coefficient $\dot{\rho}$ can be measured and it is given as

$$\dot{\rho}_E = \frac{\dot{\mathbf{E}}^-}{\dot{\mathbf{E}}^+} , \qquad (7)$$

where $\dot{\mathbf{E}}^+$ and $\dot{\mathbf{E}}^-$ are intensities of reflecting and incident waves respectively.

When we take in account expressions of $\dot{\mathbf{E}}^+$ and $\dot{\mathbf{E}}^-$ by means of β we have

$$\dot{\rho} = \left| \dot{\rho}_0 \right| \mathrm{e}^{\mathrm{j}(\varphi_0 + 2\beta x)} , \qquad (8)$$

where φ_0 is the phase in $x = 0$ and $\left| \dot{\rho}_0 \right|$ is absolute value in the same point. Because the incident and reflected wave create the standing wave, standing wave ratio (SWR)

$$s = \frac{\left| \dot{\mathbf{E}}_{\mathrm{min}} \right|}{\left| \dot{\mathbf{E}}_{\mathrm{max}} \right|} \qquad (9)$$

can be measured too and from the E_{min} position (d_{min}) it is possible to determine the phase

$$\varphi = 2\beta d_{\mathrm{min}} - \pi . \qquad (10)$$

But with regards to the definition of $\dot{\rho}$

$$s = \frac{1 - \left| \dot{\rho} \right|}{1 + \left| \dot{\rho} \right|} \qquad (11)$$

respectively

$$\left| \rho \right| = \frac{1 - s}{1 + s} . \qquad (12)$$

Having the quantities from measurements we can finally calculate the impedance as

$$\dot{Z} = \dot{Z}_0 \frac{1 + \dot{\rho}}{1 - \dot{\rho}} . \qquad (13)$$

But when SWR has such little value that it is impossible to measure it on one measuring range, we can determine it by measuring of w in the minimum of standing wave (Fig.1)

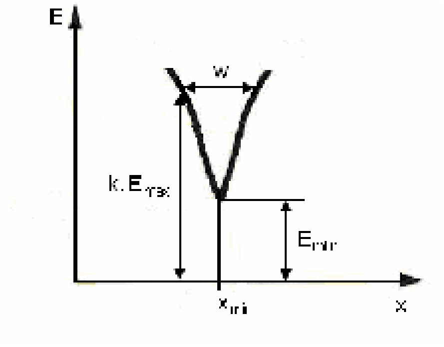

Figure 1: *The method for small SWR measurement*

and calculate it from the formula

$$s = \frac{\sin\left(\dfrac{\pi w}{\lambda_g}\right)}{\sqrt{k^2 - \cos\left(\dfrac{\pi w}{\lambda_g}\right)}}. \tag{14}$$

These formulae allow to evaluate our measurements and after plotting the graph, also to take up a stand point towards the experimental results.

3. Measuring apparatus and experimental results

The experiments were carried out on the standard laboratory microwave equipment with the connection in the schematic illustration (Fig.2).

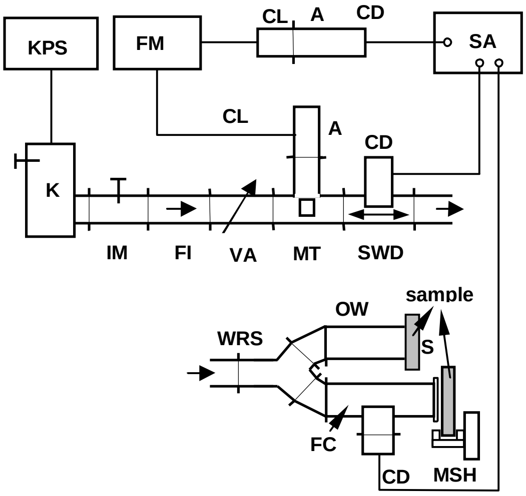

Figure 2: *Experimental set-up: K – klystron, KPS –klystron power supply, IM- impedance match, VA – variable attenuator, MT – magic T, A – adapter, CL – coaxial line, FM – frequency meter, WRS – waveguide rotation change–over switch, FI – ferrite isolator, SWD – slotted section, FC – ferrite circulator, CD – crystal detector, OW – open waveguide, SA – selective amplifier, S – sample, MSH – movable holder*

As a source of microwave signal was used the reflex klystron modulated with 1kHz signal. The measurements were carried out on frequencies from the ranges X and G band on the wave TE_{10}. The measured quantities were detected on the selective amplifier on the end of the line. The switch enables measuring both SWR and direct reflections in the same connection.

The measurements of SWR were taken with the switch position to the open waveguide (OW). OW was terminated with metal samples with the artificial slots representing cracks of the different depth and width. The samples with the defect depths from 5 to 20 mm were at disposal and the SWR was measured for every depth at each frequency by the standing wave detector. The measured and calculated values are plotted in the Fig.3.

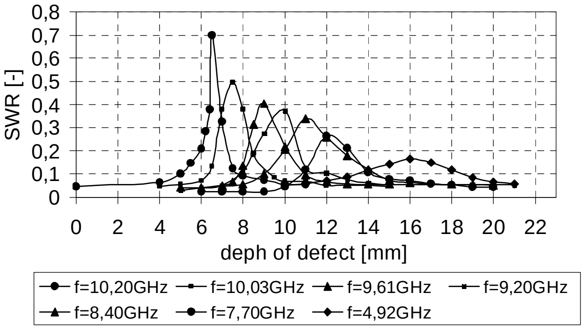

Figure3: *Dependence of SWR on the defect depth for seven frequencies*

The successive curves show quasiresonant course but in fact they represent values of waveguide terminating impedance in the waveguide–defect contact position. Formulae (11), (12) and (13) show that there is direct connection between them. From the more watchful observing the Fig.3 it was possible to assume, that individual samples at particular frequencies behave as a quarter–wave transformers. So that to confirm this assumption we further increased continuously the defect depth on a special preparation and the measured values are plotted in the separate graph (Fig.4)

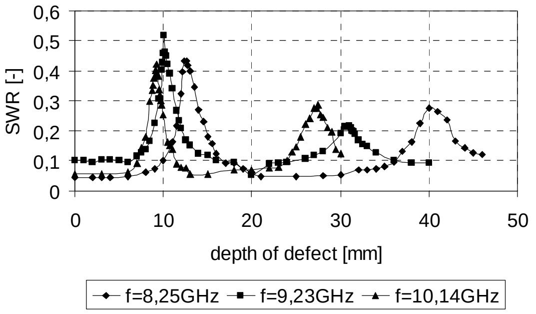

Figure 5: *Dependence of SWR on the defect depth for seven frequencies*

It can be seen from the all three courses (for frequencies 10,14GHz, 9,23GHz, 8,25GHz) that the quarter–wave transformer effect really manifests itself at individual frequencies at three multiple of $\frac{\lambda_g}{4}$.

For the more complex assessment of the measured results from the point of view of quantities with which the microwave technique operates the values of impedance were calculated (formula 13) and plotted their dependences on the defect depth at the frequency 9,23GHz, (Fig.5, 6).

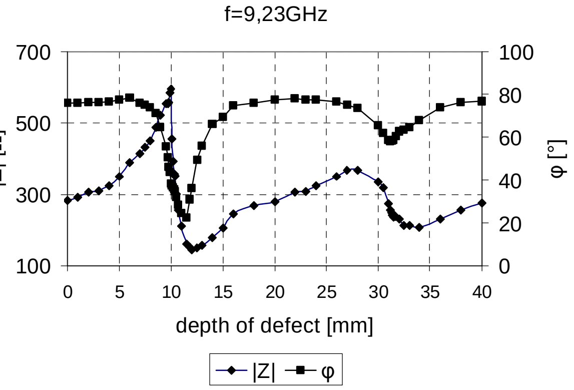

Figure 5: *Dependence of amplitude and angle of impedance on depth of defect*

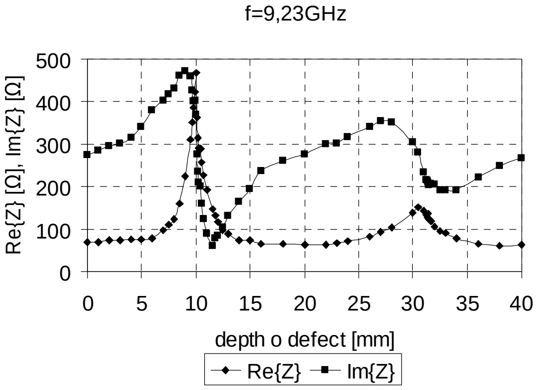

Figure 6: *Dependence of real and imaginary part of impedance on depth of defect*

An illustrative image about impedance course for the defect quarter–wave transformer affords Fig.7, where closed curves belongs to the defect depths $\frac{\lambda_g}{4}$ and $3\frac{\lambda_g}{4}$.

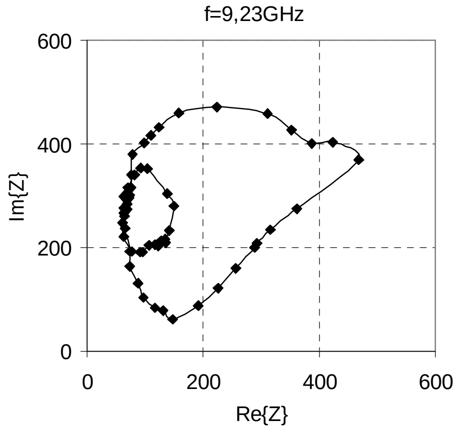

Figure 7: *Lissajouse curve for various depth of defects*

To get information how the defect width influences the reflected signal, we have measured the amplitude of the reflected signal with the moving probe position. The results for different defect widths are in the Fig.8.

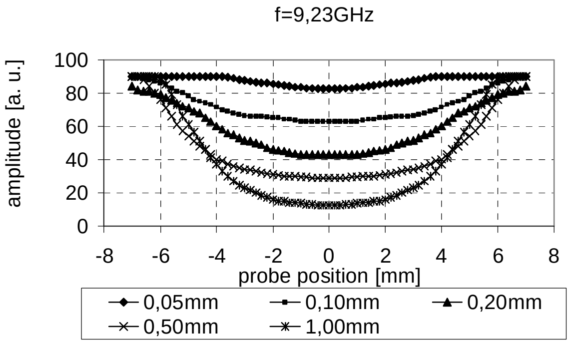

Figure 8: *Dependence of signal amplitude on probe position*

From the graph it can be seen that the sensitivity is increasing with the increasing of the defect width. The least registerabled defect width was from the interval <0,05mm ÷ 0,1mm> what was confirmed by repeated measurements, too.

With the open waveguide it could be possible to obtain information about the defect orientation. Changing the angle between the waveguide H–plane and the straight line passing along the defect we measured the reflected signal amplitude and the dependence is in the Fig.9.

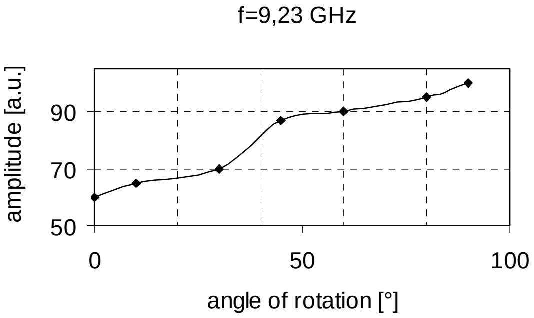

Figure 9: *Dependence of signal amplitude on angle of rotation*

4. Conclusions

The relevant literature sources mention about different surface, subsurface and stress-corrosion defects. We directed at deeper defects, which are a problem for some conventional techniques. Our work was directed towards microwave technique utilization through nontraditional way and we have paid our attention primarily to the experimental verifying of microwave utilizing for defects in metals. Cracks were tested from the point of view the waveguide techniques and on this base we could characterize it as special waveguide section and under certain conditions the defect can manifest itself as a quarter – waveguide transformer. This property allows to detect it as a quasiresonant effect and from finding this out we could state what frequencies appertain to the individual defect depths. Finally we can state that microwaves can be used for finding out crack presence, its depth, width, and orientation and in cooperation with other method they can be used as effective tool for material testing.

5. Acknowledgement

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6. References

[1] M. Pastorino, A. Massa, S. Caorsi, “A Global Optimization Technique for Microwave Nondestructive *Evaluation”, IEEE, Transaction on Instrumentation and Measurement,* Vol. 51, (2002), pp. 666-673.

[2] R. Zoughi, S. Ganchev, “Microwave NDE – State – of – the –Art Review”, *NTIAC 95 – 1, Austin, TX*, (1995).

[3] Electrical and Computer Engineering at University of Missury Rolla: Applied Microwave NDT.