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UTILIZATION OF MICROWAVES AT MATERIAL DEFECTS INVESTIGATION

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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.*

Key words: *Non-destructive testing, microwaves, crack depth, waveguides, rust*

INTRODUCTION

The article is engaged in detection of cracks in metals from the microwave theory standpoint, and so it tends to basic research. Nevertheless an example about more versatile using of Maxwell´s equations is presented on a practical case at the detection of a defect in metal, a smaller one comparing with the detector's wavelength. On the assumption starting from the wave theory applied in microwave technique a proof is given that a seeming unreability of the defect detected in such configuration is in a fact one case of electromagnetic wave spreading out in the rectifying surroundings.

On the experiments with artificial defects it is demonstrated how general relations for impedance can be used at the determining of the defect geometry.

On the basis of measurements also the influence of dielectric splits on the measuring signal is quantitatively presented.

1 THEORY

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 having a sinusoidal character with the angular frequency ω we can write

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

where $\dot{\mathbf{E}}$ is the phasor – vector of electric field intensity, $\frac{\omega}{c}=\frac{2\pi}{\lambda}$ is the phase constant for the TEM waves and λ is the wavelength in free space. On the assumption that the change of the $\dot{\mathbf{E}}$ in dependence on coordinate x has the form

$$\frac{\partial^2\dot{\mathbf{E}}}{\partial x^2}=-\beta^2\dot{\mathbf{E}} \tag{2}$$

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

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

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

$$\lambda_\mathrm{g}=\frac{\lambda}{\sqrt{1-\left(\frac{\lambda}{\lambda_\mathrm{c}}\right)^2}}\,, \tag{4}$$

where λ_c is the cut-off wavelength.

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

$$\dot{\rho} = \frac{\dot{\mathbf{E}}^-}{\dot{\mathbf{E}}^+}, \tag{5}$$

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

$$\dot{\rho} = |\dot{\rho}_0| \mathrm{e}^{\mathrm{j}(\phi_0 + 2\beta x)}, \tag{6}$$

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

$$s = \frac{|\dot{\mathbf{E}}_{\min}|}{|\dot{\mathbf{E}}_{\max}|} \tag{7}$$

can be measured and from the $\dot{\mathbf{E}}_{\min}$ position it is possible to determine the phase

$$\phi = 2\beta\, d_{\min} - \pi \tag{8}$$

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

$$s = \frac{1 - |\dot{\rho}|}{1 + |\dot{\rho}|}, \tag{9}$$

respectively

$$|\dot{\rho}| = \frac{1 - s}{1 + s}, \tag{10}$$

or

$$\dot{Z} = \dot{Z}_0 \frac{1 + \dot{\rho}}{1 - \dot{\rho}}. \tag{11}$$

Seeing that $\dot{\rho}$ as a complex quantity can be calculated from (8) and (10) we can determine $\dot{Z}$ also in the component form

$$\dot{Z} = \dot{Z}_{0mn} \frac{1 - |\dot{\rho}|^2}{1 + |\dot{\rho}|^2 - 2|\dot{\rho}|\cos\phi} + \mathrm{j}\dot{Z}_{0mn} \frac{2|\dot{\rho}|\sin\phi}{1 + |\dot{\rho}|^2 - 2|\dot{\rho}|\cos\phi}. \tag{12}$$

As all quantities on the right hand of this equation are measurable, $\dot{Z}$ can be evaluated.

2 EXPERIMENTAL RESULTS

The experiments were carried out on the standard laboratory microwave equipment, [1] with the connection in the schematic illustration in Fig. 1.

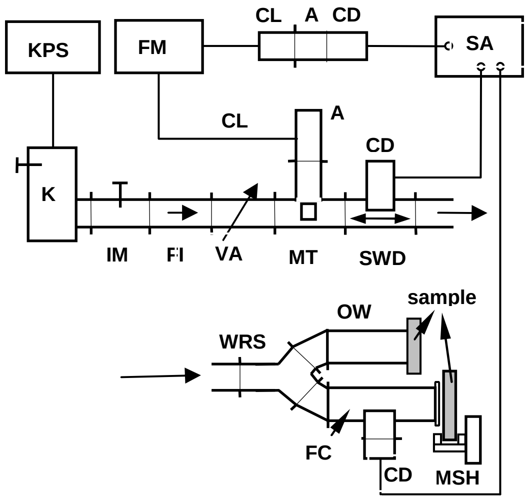

Fig.1: *Experimental set up for inhomogenities measurement, K – reflex klystron, KPS –klystron power supply, IM- impedance match, VA – variable attenuator, MT – magic T, A – adapter, CL – coaxial line, FM – frequency meter, FI – ferrite isolator, T, A – adapter, CL – coaxial line, FM – frequency meter, WRS – waveguide rotation change–over switch, FI – ferrite isolator, SWD – standing wave ratio measurement line, FC – ferrite circulator, CD – crystal detector, OW – open waveguide, SA – selective amplifier, S – sample, MSH – movable sample 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. 2.

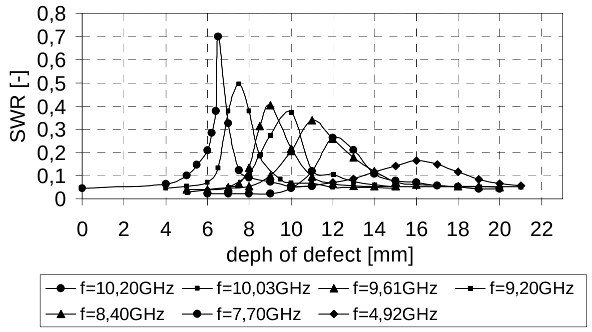

Fig. 2: Dependence of SWR on the defect depth for seven frequencies

The successive curves show quasiresonant course but in fact they represent values of waveguide terminating impedance in the waveguide–defect contact position. Formulae (9), (10) and (11) show that there is direct connection between them.

From the more watchful observing the Fig. 2 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. 3.

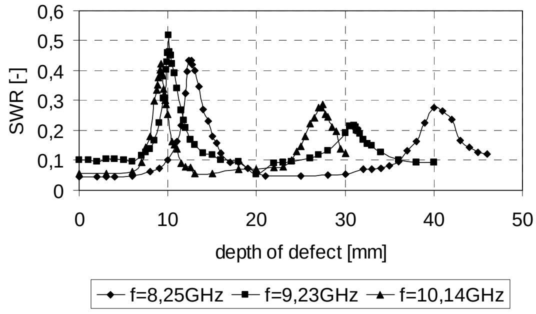

Fig. 3: Dependence of SWR on the defect depth for three frequencies

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 (12) and plotted their dependences on the defect depth at the frequency 9,23GHz, Fig. 4, and Fig. 5.

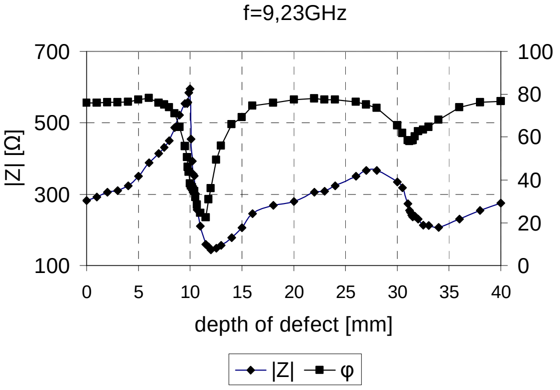

Fig. 4: *Dependence of amplitude and angle of impedance on depth of defect*

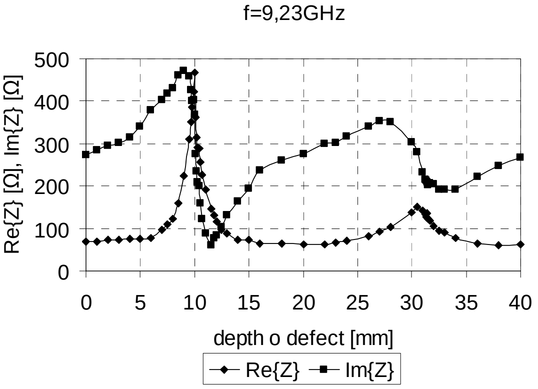

Fig. 5: Dependence of real and imaginary part of impedance on depth of defect

An illustrative image about impedance course for the defect quarter–wave transformer affords Fig. 6, where closed curves belongs to the defect depths $\frac{\lambda_g}{4}$ and $3\frac{\lambda_g}{4}$.

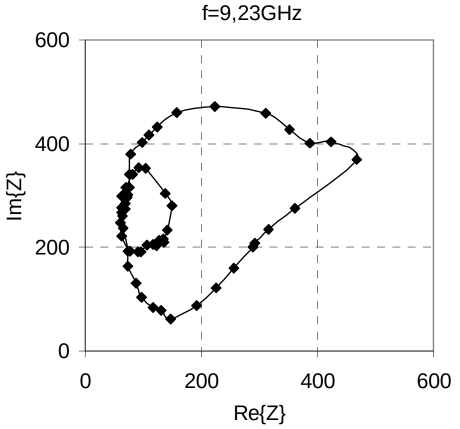

Fig. 6: Lissajouse curve for various depths of defects

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. 7.

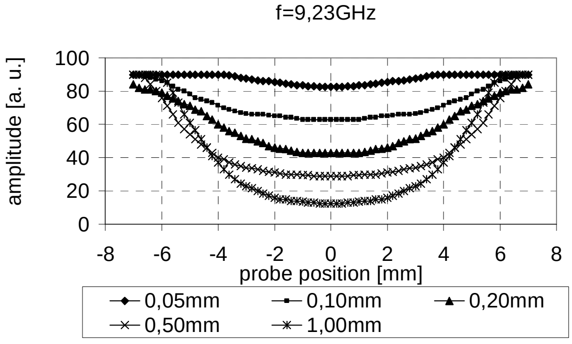

Fig. 7: Dependence of signal amplitude on probe position

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>

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. 8.

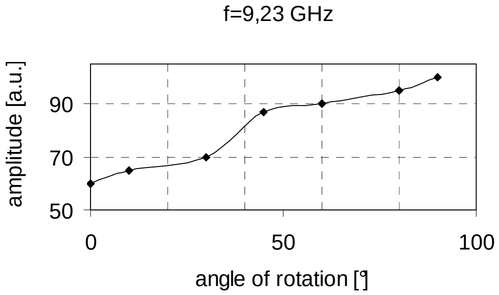

Fig. 8: Dependence of signal amplitude on angle of rotation

From the Fig. 3 it can be seen declining SWR amplitude for $n=1$ what shows that the defect behaves as a loss waveguide section. To point this fact we carried out another measurement on an artificial longer defect.

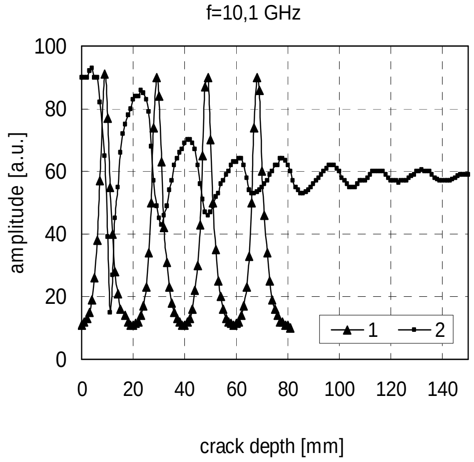

Fig. 9: Dependence of the reflected crack signal amplitude

In order to show to what extend the defect depth can influence the reflected signal amplitude we took two measurements, Fig. 9:
curve 1:the reflected signal measurement in the lossless waveguide,
curve 2: the reflected signal measurement on the sample with the defect (width of defect was 1mm).
The reflected signal was measured through the ferrite circulator, Fig. 1 and measurement were carried out for such position of the piston in the lossless waveguide which were identical with the corresponding crack depths. The comparison of the both measurements is in the Fig. 9. From this graph it is possible to form a conception about the decreasing amplitude of the reflected signal at the determining of the crack depth with $(2n+1)\frac{\lambda_g}{4}$ distant maxima.

For the reason of more complex evaluation of the defect character as a special waveguide section we also followed the shift of the SWR minimum with the enlarging defect depth. The corresponding values of the impedance were calculated from (12) and the results are in the Fig. 10. From the point of view of microwave theory the presented results bring an additional proof of the fact that for the defect investigation the microwave method can be used as well as a tried and tested microwave practice.

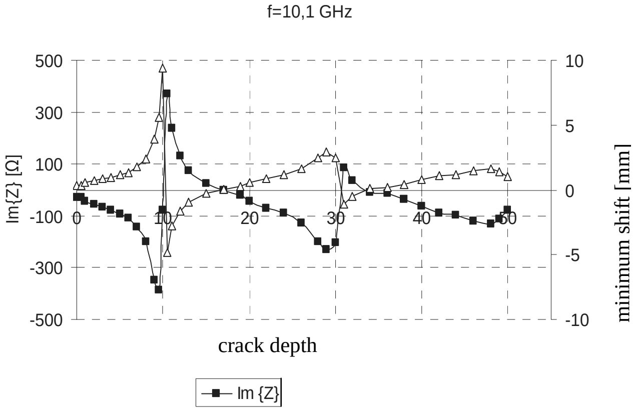

Fig. 10: Dependence of complex impedance imaginary component and standing wave minimum shift from the depth of defect

At defects detection it is necessary to admit that an older crack is partly or wholly filled with rust or another deposit and also can be covered with paint, rust or with their combination. Additional crack filling can also be water or various water solutions. These materials signify from the microwave defectoscopy point of view dielectrics which will have an influence on the defect viewed as a part of the microwave network. We followed these conditions experimentally and the obtained results are in Fig. 11 and Fig. 12.

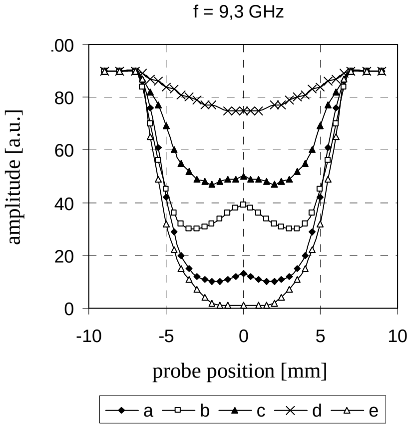

Fig. 11: Dependence of reflected signal amplitude from defect gradually filled with the rust layers (a – one layer, b – two layers, c – three layers, d – defect filled with rust, e – empty defect)

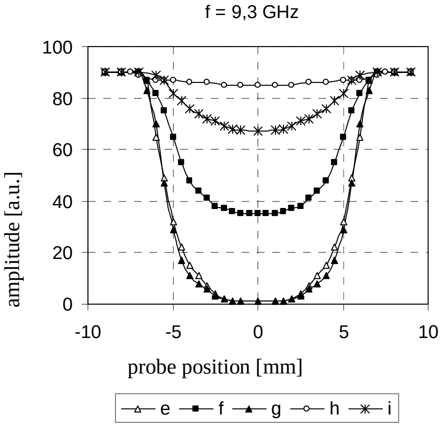

Fig. 12: Dependence of reflected signal amplitude form the presence different dielectrics in the volume and on the defect surface

In the Fig. 11 and Fig. 12 there are demonstrated courses of the reflected signal from the defect gradually being filled with rust layers (the thickness from 0,3mm in the width of 1mm). In the Fig. 11 and Fig. 12 we also present for a comparison the curve of the reflected signal course from the empty crack (curve “e”). The curve “f” represents the course of the reflected signal from the defect filled with pertinax (for the sake of the different dielectric constant), the curve “g” represent the reflected signal from the empty defect covered with a paint, the curve “h” from the defect filled with water and the curve “i” from the defect filled with paint. For every mentioned filling the complex permittivity was measured by suitable measuring method, [2].

3 CONCLUSIONS

The relevant literature sources mention about different surface, subsurface and stress-corrosion defects, [3], [4]. 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, [5] they can be used as effective tool for material testing.

Our goal was to find an interface of practical testing knowledge with the theory which is at disposal in microwave domain. With the intention of obtaining an implement not only for the detection of the defect but also for its quantitative evaluation.

The acquired experiences can be summarized in several points indicating possibilities of microwave NDT:

1. to find out the defect (with a waveguide or a coaxial probe),
2. to determine the defect orientation [6],
3. to obtain information about the defect width, [6],
4. to determine the defect depth (according to the defect impedance), [6],
5. to fix the defect depth utilizing the quarter-wave transformer effect and the attenuating characteristics.

It is worth also saying that microwaves offer additional possibilities, with regard to expanding their utilization as well sensibility and accuracy. These goals can be achieved by using higher frequencies (around 100 GHz) and more sophisticated techniques (e.g. cavity resonators).

4 ACKNOWLEDGEMENT

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