INVESTIGATION OF DEFECTS AS A LOADING IMPEDANCE OF WAVEGUIDE

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Summary The paper deals with non-destructive microwave measurement of metal defects exploiting the waveguide features at the defect shape evaluation, (e.g. quarter – waveguide transformer). As we notify in the foregoing article [1] we have paid our attention to the non-destructive investigation of metal cracks in microwave region. In this article some results concerning their evaluations regarding to microwave access are shown. From the series of measurements we present that one giving information about possible behavior of a crack.

1. INTRODUCTION

More methods for defects determination are used and we will mention only some of them. The electromagnetic nondestructive evaluation of metal surfaces can be accomplished using thin eddy current, AC field measurement, and microwave techniques. 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 [2] without the need for coating removal prior to testing. Microwave NDT can potentially generate higher resolution images with deeper penetration then the thermal and eddy current techniques [3]. More microwave techniques can be used for verifying their suitability for this purpose.

Having considered these circumstances and also with regards to the extensive area of microwaves using e.g. [4], that gives 25 investigations by means of microwaves) we decided on he 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 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 $\dot{\mathbf{E}}$ 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

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

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 used for the evaluation of the measured quantities. For the impedance $\dot{Z}$ which characterizes the conditions in waveguide the following relation 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

$$\dot{\rho} = \frac{\dot{E}^{-}}{\dot{E}^{+}}, \tag{7}$$

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

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

$$\dot{\rho} = |\dot{\rho}_0| \mathrm{e}^{\mathrm{j}(\phi_0 + 2\beta x)}, \tag{8}$$

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)

$$s = \frac{|\dot{E}_{\mathrm{min}}|}{|\dot{E}_{\mathrm{max}}|}, \tag{9}$$

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

$$\phi = 2\beta\, d_{\mathrm{min}} - \pi, \tag{10}$$

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

$$s = \frac{1 - |\dot{\rho}|}{1 + |\dot{\rho}|}, \tag{11}$$

respectively

$$\dot{Z} = \dot{Z}_0 \frac{1 + \dot{\rho}}{1 - \dot{\rho}}. \tag{12}$$

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

The relation of impedance transformation in waveguide implies from reflection transformation. In the case of lossless waveguide we get for input impedance of waveguide

$$\dot{Z}_1 = \dot{Z}_0 \frac{\dot{Z} \cos \beta\, l + \mathrm{j} \dot{Z}_{0mn} \sin \beta\, l}{\dot{Z}_{0mn} \cos \beta\, l + \mathrm{j} \dot{Z} \sin \beta\, l}, \tag{13}$$

where l is the waveguide length, $\dot{Z}$ is the loading impedance of waveguide and $\dot{Z}_{0mn}$ is the characteristic impedance for TE_{mn} mode of electromagnetic wave. If we consider loss waveguide the relation for input impedance has the form

$$\dot{Z}_1 = \dot{Z}_0 \frac{\dot{Z} \cosh \dot{k}_{zmn}\, l + \mathrm{j} \dot{Z}_{0mn} \sinh \dot{k}_{zmn}\, l}{\dot{Z}_{0mn} \cosh \dot{k}_{zmn}\, l + \mathrm{j} \dot{Z} \sinh \dot{k}_{zmn}\, l}, \tag{14}$$

where $\dot{k}_{zmn}$ is the wave number in z direction of electromagnetic wave propagation for TE_{mn} mode of electromagnetic wave.

3. EXPERIMENTAL RESULTS

The experiments were carried out on the standard laboratory microwave equipment with the connection in the schematic illustration in Figure1.

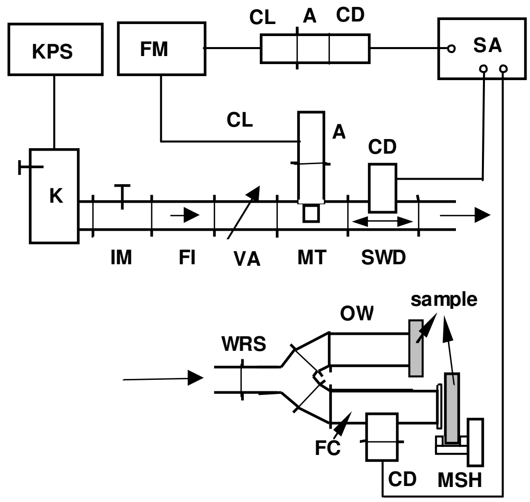

Fig. 1. Experimental set up for inhomogenities measurement, K – reflex klystron, KPS –klystron power supply, IM- impedance match, VA – variable attenuator, MT – magic T, A – adapter, CL – coaxial line, FM – frequency meter, FI – ferrite isolator, T, A – adapter, CL – coaxial line, FM – frequency meter, 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 the reflex klystron modulated with 1 kHz signal was used. The measurements were carried out on frequencies of 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 on metal samples were taken with the switch position to the open waveguide (W). Waveguide was terminated with metal samples with the artificial slots representing cracks of the different depth and width. The SWR was measured by the standing wave detector.

On the basis of our previsions measurements [5] we decided to investigate the behavior of the cracks as a special waveguide section from the point of its depth. For this purpose we have measured the dependence of reflected signal from the artificial crack on a changing depth, the width of the crack was set to 1mm. Measuring results are plotted in the Figure 2.

Chyba! Neplatné prepojenie.

Fig. 2. Dependence of the reflected crack signal amplitude

Figure 2 shows that the crack really behaves as a loss waveguide section, (plot 2). This fact enables to get information about the properties of the crack. For the comparison the same plot for the lossless waveguide is plotted, (Figure 2, plot 1).

From the measuring of SWR on the slotted line the values of the reflection coefficient and its angle were calculated and are plotted in Figure 3.

Chyba! Neplatné prepojenie.

Fig. 3. Dependence of the reflection coefficient and its phase on the crack depth

For the purpose of getting the complex microwave information about the crack also the amplitude of impedance and its phase were evaluated and are plotted in the Figure 4.

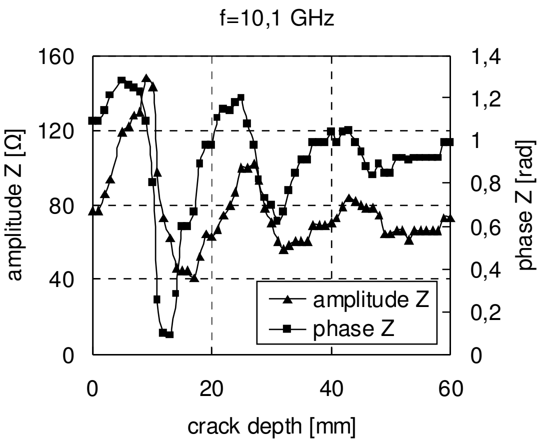

Fig. 4. Dependence of the impedance and its phase on the crack depth

Figure 5 displays Lissajous plot of the impedance of the defects with various depth

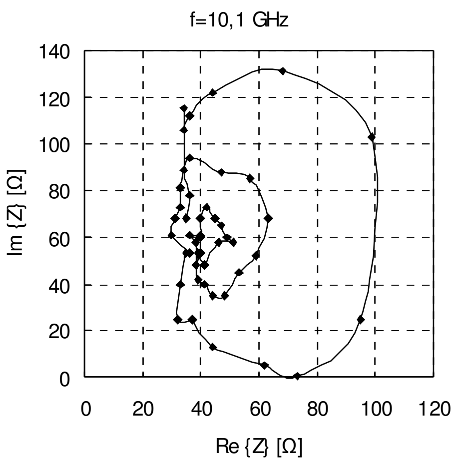

Fig. 5. Lissajous plot of the impedance for various depth of crack

From this figure it can be seen that the impedance gives information about resonance character of the crack like loss waveguide.

To get information how the defect width influences the reflected signal, we have measured the amplitude of the reflected signal with the changing probe position. The results for different defect widths are in the Figure 6. From the figure it can be seen that the sensitivity is increasing with the increasing defect width. The least registered defect width was from the interval <0,05mm ÷ 0,1mm> what was confirmed by repeated measurements, too.

Chyba! Neplatné prepojenie.

Fig. 6. Dependence of the reflected crack signal amplitude on probe position for various crack depth

The dependence of the probe distance from the crack is shown in the Figure 7. It can be seen the effect of the reflected signal phase on the crack signal amplitude.

Chyba! Neplatné prepojenie. *Fig. 7. Dependence of the reflected crack signal amplitude on probe distance for various crack depth*

4. CONCLUSIONS

The relevant literature sources mention about different surface, subsurface and stress-corrosion defects. We directed our attention at deeper defects, which are a problem for some conventional techniques. Our work was directed towards microwave technique utilization through non-traditional way and we have paid our attention primarily to the experimental verifying of microwave utilizing for defects in metals investigation. Cracks were tested from the point of view of the waveguide techniques and on this base we could characterize it as special waveguide section. 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 like a loss waveguide.

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