ENHANCEMENT OF DEFECTS IN METAL SAMPLE CHARACTERISTICS EVALUATION BY USING MICROWAVE METHODS

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Received 10th March 2009; accepted in revised form 1st April 2009

Abstract
In the paper main consideration is paid to investigation of inhomogeneities in metal sample from the standpoint of their impedance properties and reflected signal amplitude. Such application include inspecting modern materials such as composites, detecting and characterizing surface and volume flaws, and evaluating the compressive strength of cement structures. The paper deals with measurement of reflex coefficient in dependence on crack depth on metal samples on microwave frequencies from the X-band. Evaluations are made by means of quantities used in microwave technique.

Keywords: microwave non-destructive testing, waveguide method, metals

1. Introduction
In the broad spectrum of material testing methods as far as their duration of application, microwave technique plays in spite of its already proven possibilities relatively a new approach to these problems. For possible cause of this state a poor understanding of the microwave theory and practice in the non-destructive testing community is considered. However many published experiences prove broad possibilities of this method and new accesses to this problems as well as new technical possibilities make the microwave testing easily accessible. Besides that the capability of providing real-time information, makes this method suitable for on-line industrial applications.

In view of dielectric material properties and the capability of microwave signals to penetrate inside dielectric media easily the microwave testing has asserted itself in this area naturally first. In addition to that this method has asserted itself at cracks detection on metal surface and not only at finding them out but also at determining their properties. Among these also our publication concerning crack depth detection can be included [1].

In another works we aimed ourselves to finding geometry and some additional defect properties in metals. After the experimentally confirmation the fact that the defect can be examine as a special waveguide section we engaged in examination of its impedance properties enabling to obtain more precision information about the defect [2].

The next experiments were directed at the defect depth settling by utilizing of microwave knowledge. For this purpose were predominately used classical microwave measuring technique exploiting reflected signal properties either registered directly by some elements of the microwave line (e.g. ferrite circulator) or by means of standing wave ratio (SWR) measurement and subsequent adoption of measured values (impedance character, minimum standing wave shift and like that) [2].

As the microwave technique disposes of the extensive range of measuring methods, we directed our attention in next experiments at giving precision to measured results and on the one hand at the shape of the reflected signal from the defect and on the other hand at its depth.

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. For the transversal electric field having a sinusoidal character with the angular frequency $\omega$ we can write

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\[
\frac{\partial^2 \hat{E}}{\partial x^2} + \frac{\partial^2 \hat{E}}{\partial y^2} + \frac{\partial^2 \hat{E}}{\partial z^2} + \frac{\omega^2}{c^2} \hat{E} = 0,
\]

where \( \hat{E} \) is the phasor – vector of electric field intensity, \( \frac{\omega}{c} = \frac{2\pi}{\lambda} \) is the phase constant for the transversal electromagnetic (TEM) waves and \( \lambda \) is the wavelength in free space.

On the assumption that the change of the \( \hat{E} \) in dependence on coordinate \( x \) has the form

\[
\frac{\partial^2 \hat{E}}{\partial x^2} = -\beta^2 \hat{E},
\]

where \( \beta = \frac{2\pi}{\lambda_0} \) is the propagation constant and \( \lambda_0 \) is the wavelength in the waveguide, we get

\[
\frac{\partial^2 \hat{E}}{\partial y^2} + \frac{\partial^2 \hat{E}}{\partial z^2} + \left( \frac{\omega^2}{c^2} - \beta^2 \right) \hat{E} = 0.
\]

For experiments we use transversal electric (TE) waves and they are based on the reflected signal from defects. Our measurements and calculations are based on this reality exploiting the waveguide technique, where the complex reflection coefficient \( \rho \) can be measured and it is given as

\[
\rho = \frac{\hat{E}^-}{\hat{E}^+},
\]

where \( \hat{E}^+ \) and \( \hat{E}^- \) are intensities of reflecting and incident waves, respectively. When we take in account expressions of \( \hat{E}^+ \) and \( \hat{E}^- \) by means of propagation constant \( \beta \) we have

\[
\rho = |\rho_0|^2 e^{j(\phi_0 + 2\beta x)},
\]

where \( \phi_0 \) is the phase of \( \rho \) in the point \( x = 0 \) and \( |\rho_0| \) is absolute value of \( \rho \) in the same point. The incident and reflected wave create the standing wave. Standing wave ratio \( s \) (SWR)

\[
s = \left| \frac{\hat{E}_{\text{min}}}{\hat{E}_{\text{max}}} \right|
\]

can be measured and from the \( \hat{E}_{\text{min}} \) position it is possible to determine the phase of \( \rho \).

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

\[
\dot{Z}_1 = \dot{Z}_0 \frac{\dot{Z} \cos \beta l + j\dot{Y}_{\text{loss}} \sin \beta l}{\dot{Z}_{\text{loss}} \cos \beta l + j\dot{Z} \sin \beta l},
\]

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

\[
\dot{Z}_1 = \dot{Z}_0 \frac{\dot{Z} \cosh k_{\text{loss}} l + j\dot{Y}_{\text{loss}} \sinh k_{\text{loss}} l}{\dot{Z}_{\text{loss}} \cosh k_{\text{loss}} l + j\dot{Z} \sinh k_{\text{loss}} l},
\]

where \( k_{\text{loss}} \) is the wave number in \( z \) direction of electromagnetic wave propagation for TE\(_{mn}\) mode of electromagnetic wave in waveguide.

Seeing that \( \rho \) is a complex quantity we can determine complex impedance of defect \( \dot{Z} \) like terminative impedance of waveguide in the component form

\[
\dot{Z} = \dot{Z}_0 \frac{1 - |\rho|^2}{1 + |\rho|^2 - 2|\rho| \cos \phi} + j\dot{Z}_0 \frac{2|\rho| \sin \phi}{1 + |\rho|^2 - 2|\rho| \cos \phi},
\]

where \( \phi \) is the angle of \( \rho \) and \( \dot{Z}_0 \) is the characteristic impedance of waveguide. As all quantities on the right hand of equation (9) are measurable [3], [4] \( \dot{Z} \) can be evaluated.

The successive curves for individual defects show [1] quasiresonant course but in fact they represent values of waveguide terminating impedance in the waveguide–defect contact course. It is possible to assume, that individual samples with defects at particular frequencies behave as a quarter–wave transformers. The quarter–wave transformer effect manifests itself at individual frequencies at three multiple of \( \lambda_0 \), where \( \lambda_0 \) is the length of wave in waveguide, Fig. 1.

![Fig. 1. Dependence of SWR from the defect depth for different frequencies with the chart of quarter-wave transformers effect](image-url)
3. Experimental results

Our attention was aimed namely at the testing of metal materials. On the first sight it was little probable that, for example with a probe made from an open waveguide, it could be possible explicitly to find a defect which represents only a tiny fraction of the conducting surface radiated with the microwave signal from the reflected part of this signal. After realizing that the defect can be considered as a terminated impedance of such probe (open waveguide), we can get information about the character of this impedance (that is about the defect complex impedance character). For the better “contact” with the directly measurable quantity we present only an example of standing wave ratio measurement in dependence on the defect depth. The relation between SWR and the reflection coefficient and subsequently complex impedance give a similar dependence, where complex impedance is the terminating impedance of the waveguide, in our case of the defect as a waveguide section.

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

As a source of microwave signal was used the reflex klystron modulated with 1 kHz 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 standing wave ratio (SWR) in waveguide were taken with the switch position to the open waveguide (W). The SWR was measured for every depth at each frequency by the standing wave detector.

Samples were made in such way to be as much as possible similar to the real crack and simultaneously to provide a possibility for quantitative processing and evaluation. That is, the samples were made from steel plates 5x4x1.5 [cm]. Their areas should have overlapped the waveguide cross-section (22.5x10 [mm]) and in every sample there was filed a slot with the width 1 mm and length 20 mm representing an artificial crack. These samples were located in front of the empty waveguide without any other termination (open waveguide - OW) at the distance of 1 mm and their longitudinal sections were parallel to the longer side of the waveguide.

For the purpose of getting the complex microwave information about the crack also the amplitude of impedance and its phase were evaluated [1], and are plotted in Fig. 3 and in complex plane in Fig. 4.


![Fig. 3. Dependence of real and imaginary impedance component from the probe position](image)

![Fig. 4. Dependence of impedance angle from the probe position in complex plane](image)
The dependence of complex impedance angle of defect in metal sample is shown in Fig. 5 for various defect depths. Each defect has its own position on the closed curves and decreasing diameter of two closed curves is connected with the fact, that the individual defects represent themselves the attenuation waveguides.

![Fig. 5. Dependence of complex impedance angle from various defect depth (d) in complex plane](image)

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 Fig. 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.

![Fig. 6. Dependence of the reflected crack signal amplitude on probe position for various crack depth](image)

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. 7.

![Fig. 7. Dependence of signal amplitude on angle of rotation](image)

The dependence of the probe distance (liftoff) from the crack is shown in Fig. 8. It can be seen the effect of the reflected signal phase on the crack signal amplitude.

![Fig. 8. Dependence of signal amplitude from liftoff](image)

In order to show to what extends 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 liftoff [cm] 1 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 \( (2n+1) \frac{\lambda}{4} \) 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 (8) 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.

Conclusions

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 [1]. Finally we can state that microwaves can be used for finding out crack like a loss waveguide and not only for depth but also for width and orientation of the defect assessment.

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:
- to find out the defect (with a waveguide or a coaxial probe),
- to determine the defect orientation,
- to obtain information about the defect width,
- to determine the defect depth (according to the defect impedance),
- 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).

Acknowledgement

The author would like to thank MSc. Pavol Žirko director of High School for Agriculture and Fishing in Mošovce for technical help at realization of experiments.

The work has been done in the framework of Grant VEGA 1/0761/08 “Design of Microwave Methods for Materials Nondestructive Testing” of the Ministry of Education of the Slovak Republic.

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