A NEW TECHNIQUE FOR SIZING CRACKS IN METALS, UTILIZING AN INDUCED SURFACE MAGNETIC FIELD

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INTRODUCTION

The new technique, introduced in this paper, has originated in the course of development of an inducing mechanism for use with the ac field measurement instrument used in detection and sizing of cracks in metals[1]. It had been known for some time that the application of an inducing mechanism capable of producing the required uniform field over the surface of the metal would add to the advantages of the ac field measurement (ACFM) technique[1,2]. This led to some activities in identifying current carrying structures which can fulfil this requirement. One structure proposed consists of two parallel wires forming a U shape which can be readily integrated with the ACFM probe, Fig.1. In practice, in order to maintain the original characteristic of the induced surface field produced by this inducing arrangement, the feeding terminals and the related wiring should be located adequately far from the metal surface.

It was found in practice that when properly designed, the above mentioned inducing mechanism can produce locally an approximately uniform

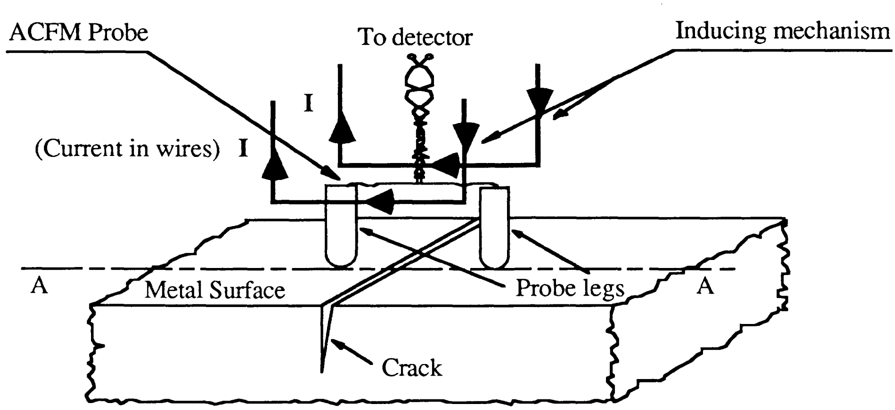

Fig. 1 ACFM probe together with a two-wire inducing mechanism.

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surface field. However, to accurately examine the effect of this inducing arrangement on sizing cracks by the ACFM technique, a theoretical assessment of the distribution of the induced surface potentials about a long uniform crack is deemed necessary. For this purpose, a mathematical model is developed. This modelling helps us to build an accurate picture of the behaviour of the field at the crack edge, showing that the induced surface field is discontinuous at the position of crack. This effect does not occur when the surface field is produced by injecting the current rather than inducing it into a cracked metal.

The new technique proposed here for detection and sizing of cracks in metals exploits the properties of the sudden change of the surface magnetic field at the crack edge. The surface field in this technique should be produced by U-shaped current carrying wires located at some distance above the metal surface. This technique relies on measurements of the magnetic field and makes use of an eddy-current probe capable of coupling to the desired component of the field at metal surface. As will be shown later, measurements of the surface magnetic field at the two sides of a one dimensional crack provide sufficient data which can, by means of a set of curves computed for the inducing mechanism used, be inverted to give the crack size. Athough still in its infancy, the new technique is believed to be able to offer several advantages over the eddy current method, including ease of use, simplicity in the inversion process and accurate sizing of cracks.

This paper is essentially concerned with the review of the theoretical and experimental investigations so far carried out on this new technique. It also presents a brief outline of the solution of the mathematical model developed for describing the field behaviour around a long uniform crack. The mathematical details of the solution will be presented in a separate paper.

THEORY OF THE INDUCED SURFACE FIELD ABOUT A CRACK

The model considered for the analysis of the field induced on the surface of a cracked metal by the two-wire U-shape inducing mechanism, is shown in Fig.2. In this model it is assumed that the metal is flat and semi-infinite, the crack is one dimensional, the wires are infinitely thin, and the current skin depth in the metal concerned is negligible. The latter condition calls for the operating frequency to be sufficiently high. This implies that the component of the magnetic field normal to the metal surface is also negligible everywhere, even on the faces of the crack. Under this condition and in the absence of any flaws in the metal, the surface magnetic field due to the inducing mechanism, which in this paper is termed the incident field, can be obtained through the method of images[3]. This method is applied and the metal is replaced by the images of the current carrying wires. At the symmetry plane coincident with the metal surface, the incident magnetic field H_i is obtained by doubling the field strength due to the inducing mechanism itself. Considering that the metal has finite conductivity σ, the induced surface electric field can be obtained from H_i through the well-established expression for surface fields

$$E = (Y/\sigma)\ \hat{z} \times H \qquad (1)$$

In this equation, $Y = (j2\pi\mu\sigma f)^{1/2}$ and μ is the metal permeability.

The presence of a crack in the metal alters the distribution of the incident field and a new surface field emerges. In view of the fact that the magnetic field is free from the component normal to the metal surface, it can be concluded that the surface electric field E can be described in

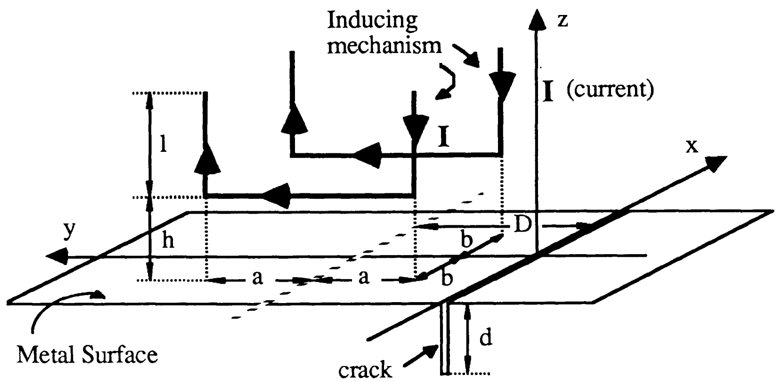

Fig. 2 Model used in the theoretical analysis.

terms of a surface potential U such that

$$E = \text{grad}\ (\ U\ ) \qquad (2)$$

where U is the solution to Laplace's equation

$$\text{div grad}\ (\ U\ ) = 0 \qquad (3)$$

subject to boundary conditions. The solution to the above equation is sought through the application of the unfolding technique[1,2]. In this technique, the crack is unfolded and made coplanar with the metal surface, thus leading to four solution domains in one plane. The electric field in the domains corresponding to the metal surface can be stated in terms of two fields, the incident field E_i and the scattered field E_s, where the latter represents the perturbation due to crack in the incident field. This decomposition simplifies the solution by posing the problem initially in terms of the scattered field. The new problem to solve is shown in Fig.3 where V is the scalar potential function for the scattered electric field. Using the Fourier transform technique, the solution to V was obtained. The full description of the surface electric field is then found by the superposition of the scattered and the incident fields, from which the associated surface magnetic field via Eq.(1) immediately follows.

The final expressions for the induced surface field are involved and require computer implementation in order to obtain the field distribution. A computer code in Fortran 77 is developed , capable of computing the surface electric and magnetic fields at any arbitrary point over the metal surface and, if required, even over the crack faces. It can also produce the distribution of the surface potential differences as picked up by an ACFM probe.

THEORETICAL AND EXPERIMENTAL RESULTS

The above mathematical modelling was originally developed as a means of quantifying measurement errors in sizing cracks by the ac field mesurement technique, when the surface field is induced by two U-shape current carrying wires. Accordingly, tests of the theory in this respect were initially performed. These tests were mostly concerned with the

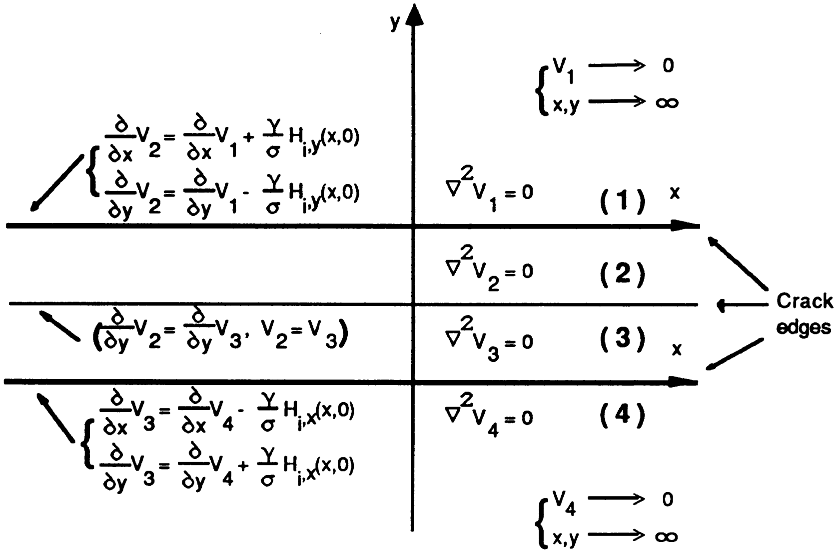

Fig. 3 Illustration of the problem for the scattered potential V.

comparison of the theoretical and practical distributions of surface potential differences along the y-axis about various saw-cut notches in mild steel test blocks. It was during these tests that it came to light that the surface electric field component E_y along the y-axis has a discontinuous behaviour at the crack edge. Given Eq.(1), the induced surface magnetic field component H_x is expected to behave similarly. This is thoroughly investigated for various crack sizes and various positions of the inducing mechanism, with the help of the developed computer program. In this theoretical simulation, the surface field is assumed to be produced by the inducing mechanism shown in Fig.2 with arbitrary specifications a=25 mm, b=10 mm, h=37 mm, l=120 mm. As a result of this investigation, a collection of field plots is generated of which some are shown in Fig.4. Examination of these graphs leads to several interesting conclusions:

(i) At the crack edge, H_x along the y-axis is discontinuous.
(ii) The magnitude of this discontinuity, ΔH_x is a function of the crack depth; in fact the deeper the crack, the larger the value of ΔH_x.
(iii) At the two sides of the crack edge, the slopes of H_x are generally different.
(iv) For a particular crack size, ΔH_x is a function of the position of the inducing mechanism with respect to crack.

The dimensions of the inducing mechanism also affects ΔH_x. For instance, the effect of length a of the specified inducing mechanism on ΔH_x has implicitly appeared in Fig.5. This figure shows the relationship between the crack depth d and the relative change of H_x at the crack edge defined as

$$R_m = \Delta H_x / H_{x2} \qquad (4)$$

In the above definition, H_{x2} refers to the magnitude of the field as shown in Fig.4. As seen in Fig.4 and Fig.5 when a/d is very large, ΔH_x tends to be very small.

The above theoretical results are confirmed through a series of tests conducted over two mild steel test blocks containing several saw-cut

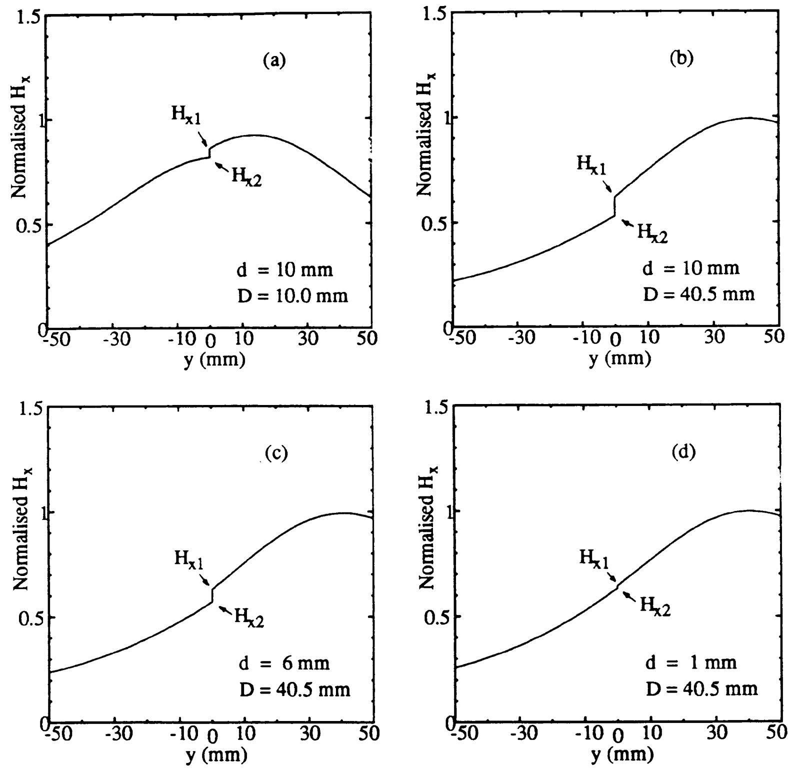

Fig. 4 Theoretical behaviour of induced surface magnetic field (H_x) along the y-axis for various values of d and D. These curves are normalised to the maximum value of H_x when no crack is present in the metal.

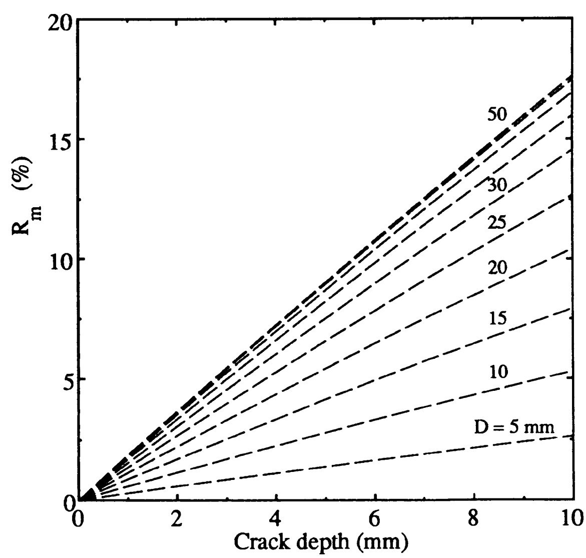

Fig. 5 Variation of R_m(%) with crack depth for different positions of the inducing mechanism.

notches of different depths. In these experiments, an eddy-current probe similar to that reported in[4] is used to measure the surface magnetic field. The inducing mechanism involved in these tests has similar specifications to those specified in the theoretical simulation. It is excited by the 1.6 kHz ac current source of the ACFM instrument developed in our laboratory. Note that at 1.6 kHz, the current skin depth in mild steel is about 0.3 mm in which case the electromagnetic fields inside the test blocks can be assumed to be virtually confined to the surface. The same ACFM instrument is used to detect the probe signal. Various preliminary tests on the performance of the probe convinced us that when it is in close proximity to the surface, it can pick up the desired component of the surface magnetic field with adequate accuracy. In the experiments performed, the probe is scanned automatically and rapidly using a motorised scanner.

Results of those experiments devoted to investigating the surface magnetic field along the y-axis about a 10 mm deep notch are shown in Fig.6. In these experiments the inducing mechanism is placed at positions D=10 mm and D=40.5 mm with respect to the notch. These experimental results, Fig.6 , clearly substantiate the validity of the theoretical modelling, when compared with Fig.4.a-b. The experimental traces are also checked quantitatively to assess the accuracy of the theory. Allowing for experimental error, good agreement between the theory and the experiment is always achieved. The experimental results, however, indicate that the change of the magnetic field at the crack edge is not as sharp as that predicted theoretically. This effect could be attributed to several factors including the finite distance of the probe from the metal surface, and the finite time constant of the ACFM instrument. Nevertheless, since the determining factor in sizing cracks with this method is the magnitude of the change of the magnetic field at the crack edge, the mentioned effect is not expected to influence the measurement accuracy significantly.

Further scans are then made about 2 mm, 3 mm, 8 mm and 10 mm notches. In these experiments, the inducing mechanism is located symmetrically, first between 2 mm and 3 mm notches and then between 8 mm and 10 mm notches. This arrangement allows a simultaneous examination of the effects of two notches on the induced surface magnetic field. The storage scope traces of these experiments are shown in Fig.7, indicating the relationship between the depth of the notch with the signal jump at the notch edge.

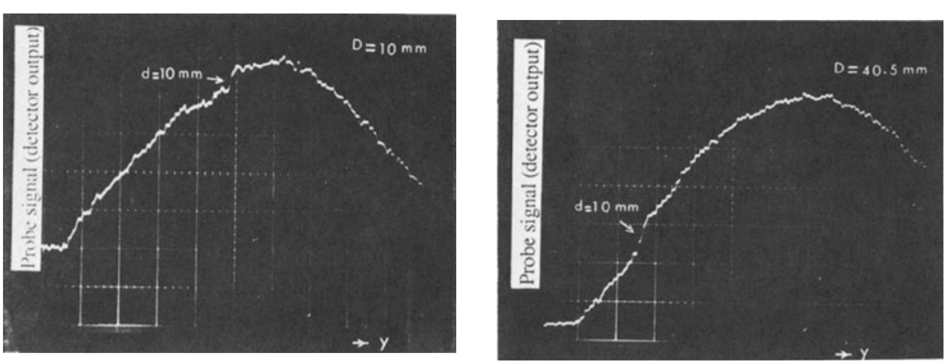

Fig.6 Probe signals about a 10 mm saw-cut notch. Arrows indicate discontinuities in signals.

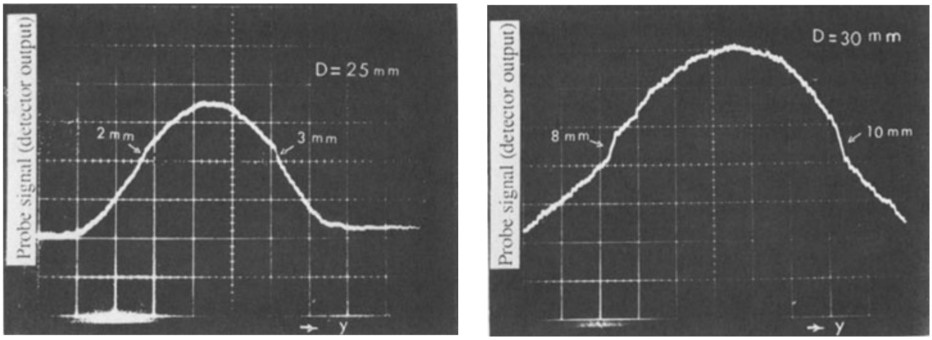

Fig. 7 Probe signals about four saw-cut notches. In these tests, each pair of notches is located symmetrically with respect to the inducing mechanism.

With the help of the chart provided, Fig.5, the value of R_m for each of the above cases is inverted and the measured depth of the notch together with its true depth is recorded in Table I. From this table, it is clear that although from the practical point of view, the agreement between the measured and true depths of the notches is generally satisfactory, for shallow cracks the errors recorded are somewhat high. After some further tests, it is concluded that these unexpected high errors may stem from the edge effect[5]. The effect appears to be more influential in distorting low level signals produced by shallow notches. The edge effect could be alleviated by increasing the frequency or/and reducing parameters h and a associated with the inducing mechanism. Implementation of the latter alternatives would produce stronger signal jump at the crack edge. These are yet to be investigated.

CONCLUSIONS

In this paper, a new technique for sizing cracks in metals is proposed. This technique is based on measurements of the induced surface magnetic field at the two sides of the crack edge using a non-contacting probe. The surface field in the metal under inspection is produced by an inducing structure consisting of two U-shaped wires in which an ac current of high frequency flows. For sizing long uniform surface breaking cracks by the presented technique, a mathematical model of the problem was initially developed. This modelling shows that the relative change of the

Table I

Actual depth (mm)	10	8	3	2
Measured depth (mm)	10.36	7.06	3.47	2.35
Error (%)	3.6	-11.8	15.8	17.9

surface magnetic field at the crack edge is a function of the crack depth, of the position of the inducing structure with respect to the crack and of the dimensions of the inducing arrangement. By means of several saw-cut notches made in large mild steel flat plates, the accuracy of the mathematical modelling through several experiments is confirmed. The experimental conditions and the detecting system including the probe are breifly discussed. For a particular U-shape inducing mechanism, a chart is provided for the purpose of the inversion. Using this chart, depths of several saw-cut notches are measured by the new technique. These measured depths are generally found to be in agreement with the true depths. However, for shallow notches, the measurement errors are observed to be more than those for deep notches. After further experiments, this discrepancy is attributed to the omission of the edge effect in the theoretical modelling. Ways of reducing this effect on the measurement accuracy are proposed.

ACKNOWLDEGEMENT

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REFERENCES

1. R. Collins, W. D. Dover and D. H. Michael, in Research Techniques in Nondestructive Testing, Vol. VIII, R. S. Sharpe, ed., pp.211-267, Academic Press, London, 1985.

2. R. Collins, D. Mirshekar-Syahkal and D. H. Michael, in Review of Progress in Quantitative Nondestructive Evaluation, D. O. Thompson and D. E. Chimenti, eds., pp.1255-1268, Plenum Press, New York, 1983.

3. Edward C. Jordan and Keith G. Balmain, Electromagnetic Waves and Radiating Systems, Prentice-Hall, New York 1969.

4. R. O. McCray, D. W. Oliver, K. H. Silverstein and J. D. Young, IEEE Trans. in Magnetics, Vol. Mag-20, No.5, pp.1986-1988, 1984.

5. D. H. Michael, R. T. Waechter and R. Collins, Proc. R. Soc. A381, pp.139-157, 1982.