Simple Electromagnetic Detection of Variations in Properties of Metal Surfaces

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***Abstract*—Recently, a significant improvement in the sensitivity of the nonuniform ac field measurement technique for the detection of cracks was reported. In this paper, the results of the application of the improved technique in the detection of heat-affected zones and ground welds are presented and briefly discussed. In such applications, the use of a long probe is essential.**

***Index Terms*— AC field measurement, eddy-current NDE/T, ground-weld detection, heat-affected zone detection.**

I. INTRODUCTION

THE ELECTROMAGNETIC nondestructive evaluation of metal surfaces can be accomplished using thin-skin eddy current (EC), ac field measurement (ACFM) and microwave techniques [1]–[3]. In these techniques, a coil, a wire loop, or a waveguide excited by a high-frequency source sets up the incident field. The magnetic field scattered by surface defects is used to interpret the surface condition.

This paper is concerned with a new application of the ACFM technique. The early version of the ACFM technique is based on the uniform incident field [2], [4]. Although this arrangement greatly simplifies the field-flaw modeling, in practice, it suffers from two major problems: limited sensitivity to long cracks and problems with setting up a uniform field. To alleviate these shortcomings, the use of a local nonuniform interrogating field was proposed [5] which subsequently led to the development of a highly sensitive ACFM technique based on the null field concept [6]. This development has improved the sensitivity by about 30 dB.

In the high-sensitivity ACFM method, a region of the magnetic field of the rectangular coil (the inducer), which possesses an odd symmetry, is exploited for positioning the probe [6]. In this field region, when properly orientated, a single probe acts as a differential probe. Therefore, a large signal amplification is possible before the detector saturates. However, this is not the only reason for achieving the high sensitivity. It was found that the phase distribution (in addition to the amplitude distribution) of the field in the vicinity of the metal surface near the two ends of a rectangular inducer is affected by the crack. The phase change leads to a strong field-flaw interaction and, hence, to a large crack signal which was observed both theoretically and experimentally [7]. This phase change, which occurs over a distance of the order of the size of the inducer, should not be confused with that associated with the crack edge. The latter occurs only at distances of the order of the skin depth from the crack which is very small when the frequency is very high.

In a more recent development, we introduced the current-carrying rhombic wire loop as an alternative inducer for high-sensitivity ACFM [8]. This inducer has the virtues of the rectangular coil with an additional advantage of flatness that makes it attractive for some applications like fabrication of long probe arrays. The use of the rhombic wire loop has been very successful. It allowed reliable detection of 50 μm deep scratches on mild steel [8] and cracks of about 0.5 mm at a probe stand-off of about 8 mm.

So far, the high-sensitivity ACFM has been mainly applied to detect surface breaking cracks in metals. In this paper, the potential of this simple electromagnetic technique in the detection of heat-affected zones and boundaries of ground welds are presented, and the requirements for a reliable detection are addressed. The application of the work is in the predication of zones where crack initiation and metal failure may occur.

II. EXPERIMENTS

The experimental set up is shown in Fig. 1(a). The high-frequency ac source drives the rhombic inducer. The linear wire-wound probe, attached below the inducer along its major axis, Fig. 1(b), picks up the magnetic field tangential to the metal surface. The signal is initially amplified by a low noise instrumentational amplifier, then fed to a lock-in amplifier, and finally arrives at a two-channel digital oscilloscope. The inducer-probe assembly, attached to the motorized x-y table, scans the work-piece under computer control.

The field pattern of a rhombic inducer close to a metal surface when operating at a high frequency is shown in Fig. 1(c). The normal component of the field at the metal surface is very small and almost negligible. Also, its tangential component is null along the center line perpendicular to the inducer plane, Fig. 1(c). Ideally, the probe is located symmetrically with respect to the center line along the major axis of the inducer. In this position, the probe is absolutely balanced, and there should be no signal at the detector output. This arrangement of the probe and inducer eliminates the balancing bridge (which is common in eddy-currentsystems) and, hence, removes its problems from the measurement system. In practice, the deviation of the probe from its ideal position and the existence of some normal field, threading a nonideal linear probe as well as the limitation on the amplifier

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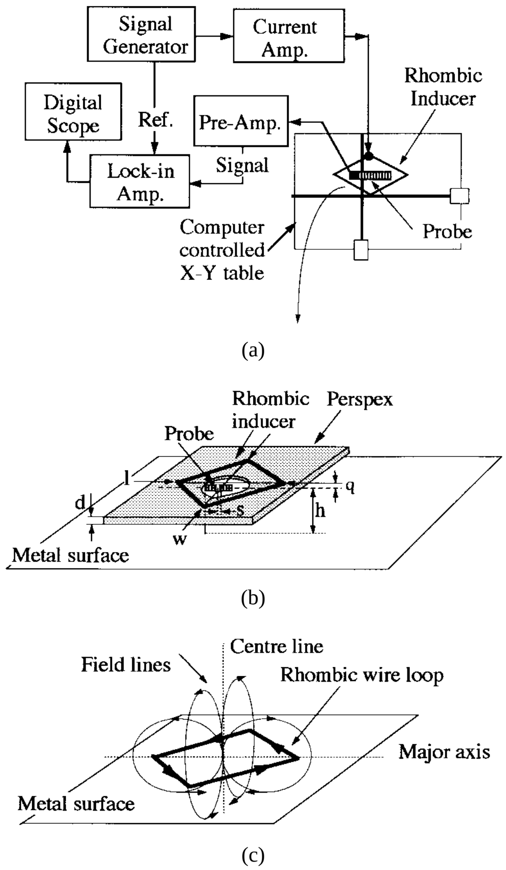

Fig. 1. (a) The experimental setup, (b) the linear probe and the rhombic inducer; $w = 11$ mm, $l = 21$ mm, $d = 3$ mm, $h = 0.84$ mm, $q = 2.4, s \approx 0$ mm (probe symmetry offset), two-layer wire-wound probe of 260 turns and 13.5 mm length, probe core radius $= 0.44$ mm and probe wire gauge $= 0.0032''$, and (c) the magnetic field around rhombic wire loop parallel to a metal surface.

common mode rejection ratio, would create a residual signal at the probe output. The dimensions of the inducer and probe used in the experiments as well as other useful parameters are shown in Fig. 1(b).

Since a heat-affected zone does not have a sharp boundary, the probe had to be long. A long probe ensures the integration of minute changes in the surface magnetic field along the probe and, hence, leads to a detectable signal at the probe output. This requirement is not important in crack detection by the same technique, because of the abrupt nature of the crack boundary. In order to enhance the phase difference between a heat-affected zone and its surroundings and, hence, to boost the signal more, a further requirement is the use of an appropriate operating frequency. Very high frequencies (when the tangential field can be effectively approximated by an image solution) [9] or very low frequencies (when the phase of the magnetic field is almost constant along the probe length) should be avoided. The range of operating frequencies may be determined experimentally or by using a computer program [7].

The first experiment was performed over a duralumin plate heated at two positions for 3 s with a oxyacetylene torch of 1.5 mm diameter. The operating frequency was 20 kHz. The results of a linear scan of the plate when the probe traversed

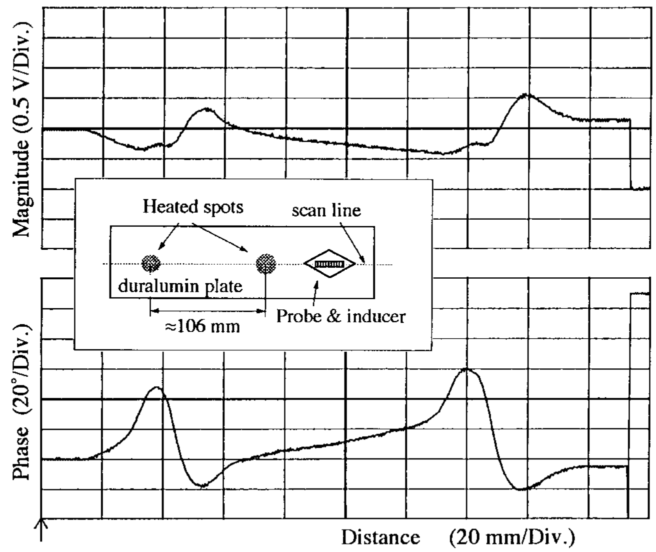

Fig. 2. Magnitude and phase of signal from the scan of the heat-affected zones in the duralumin plate.

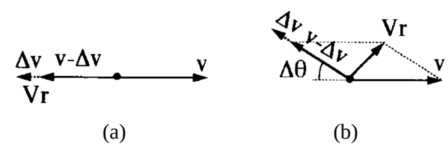

Fig. 3. Qualitative illustration of the enhancement of the probe signal (Vr) due to the small phase difference: (a) no phase difference present and (b) a small phase difference present.

the heated locations is shown in Fig. 2. A large but smooth phase change (about 80°) is apparent in the signal phase. This large phase change is one of the characteristics of the technique [6]–[8]. As mentioned earlier, the phase change is caused by a small phase difference produced in the two halves of the long probe symmetrically located with respect to the center line. This small phase difference is also responsible for the discernible amplitudes in Fig. 2. In Fig. 3, the effects of the phase difference are shown using vectors.

In the second experiment, part of a rectangular aluminum block was removed in the whole width of the block, Fig. 4. It was then filled with aluminum weld and ground until flush with the surface of the block. The approximate dimensions of the weld affected region are shown in Fig. 4. The results of a normal scan of the welded region (i.e., the probe direction is normal to the weld line) are shown in Fig. 4. The phase and magnitude signals are fairly abrupt, as expected, because of the sudden change in the characteristics of the two metals. The signals show the quality of the boundary of the weld as well as that of the welded area at the metal surface. As Fig. 4 shows, the signals are fairly constant between the two peaks of the magnitude and between the peak and trough of the phase. This is because the welded area is longer than the probe length. More importantly, comparing these constant levels with those associated with the outside of the weld, one can infer that the system is appropriate to detect variations (or the rate of change) in electrical properties of metals. Finally, the phase and amplitude signals in Fig. 4 are markedly different from

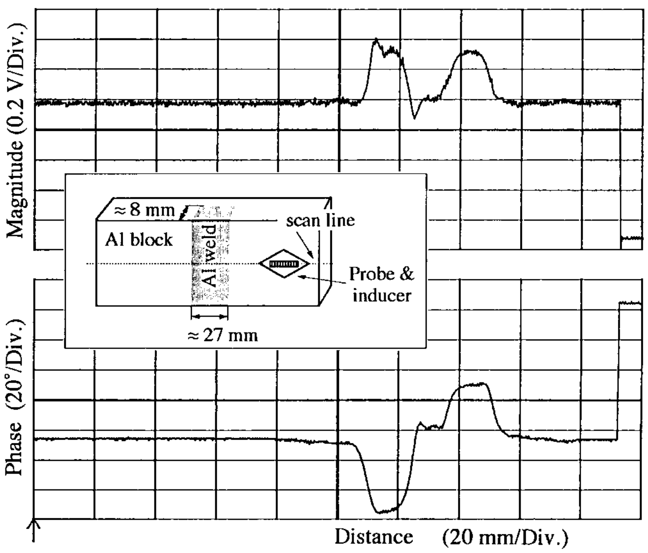

Fig. 4. Magnitude and phase of signal from the scan of the welded area in the aluminum block.

those in Fig. 2 caused by the heat effect. The differences between the two signals may be exploited to distinguish between these two cases.

III. Conclusion

Results of the application of the high-sensitivity ACFM technique to detection of heat-affected zones and ground welds are presented. The phase and magnitude signals for a heat-affected zone shows gradual variation, whereas those of a welded region change abruptly, from which the weld boundary can be reliably determined. In such applications, since changes in metal properties are small, the use of a long probe is essential. The technique may be used for quality control where the conductivity and/or permeability variations in metals are to be monitored as well as for quality control of welding.

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