A COMBINED ACFM-SMFM SYSTEM FOR REAL-TIME DETECTION AND SIZING OF SURFACE CRACKS IN METALS

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INTRODUCTION

In some applications such as quality control of metal components or inspection of large metal structures, inspection systems with rapid scanning capability are required. Of particular interest are systems capable of real-time detection and sizing of surface breaking cracks in metals. Since such systems have to perform the data processing in the course of scanning, they should be based on NDE techniques with easy detection and inversion capabilities. One technique with these virtues is the alternating current field measurement (ACFM) technique [1]. In this technique, a high frequency uniform field is made incident on the work-piece and the resulting surface potential is sampled using a two-leg contacting probe. The crack signal is essentially a rectangular pulse, Fig. 1. For long cracks it can be shown that the crack depth can be determined from the crack signal using the simple expression

$$d = \frac{V_2 - V_1}{V_1} \cdot \frac{\Delta}{2} \tag{1}$$

where V_1 and V_2 are voltages picked up by the probe just before and just after the crack, Fig. 1, and Δ is the probe length. For a non-uniform crack or a non-uniform incident current, however, the above expression is not accurate. In such cases the measured depth d_m resulting from (1) should be modified using a multiplier. Multipliers are based on mathematical models relating d_m and d for different crack shapes and for different incident fields [1].

Although the ACFM technique is sufficiently simple to be considered for the development of a rapid scanning system with a real-time crack signal analysis capability, it suffers from two basic problems. First, the ACFM technique is a contacting technique. Therefore, the loss of contact due to oxidisation of the metal surface or existence of nonconducting particles on uncleaned surfaces affects its reliability. Second, it is not easy to establish a uniform surface field on the work-piece. In the conventional ACFM technique, a local uniform field is achieved by attaching the current cables to the test specimen at some distance from the inspection zone. For obvious reasons, this technique is not suitable for a scanning system. In a different technique, the so-called current induction technique, a current carrying wire or a group of wires is positioned horizontally above the metal surface in order to produce the surface field. The surface field produced by this technique is not uniform, unless the inducer consists of a large number of long wires in a plane parallel to the surface.

To enhance the reliability of the ACFM technique in rapid scanning systems with real-time detection and sizing capabilities, a second NDE technique may be employed in the inspection process to ensure that no crack is left undetected due to loss of contact. This back-

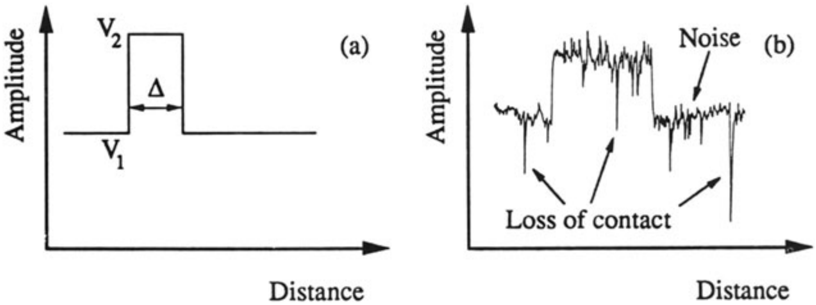


Fig.1 Typical ACFM crack signal; a) Theory, (b) Experiment.

up technique should be a non-contacting one and preferably be as simple as the ACFM technique so that it does not impose a significant burden on the signal processor. In the earlier works [2,3] we reported a non-contacting technique, the surface magnetic field measurement (SMFM) technique, which is based on the measurement of the magnetic field induced by a pair of U-shaped current carrying wires at the surface of the work-piece. In the SMFM technique, a crack produces a discontinuity in the surface field. A tape-head eddy-current sensor can be used to detect the discontinuity. A typical crack signal is shown in Fig. 2. The magnitude of the discontinuity is related to the crack depth, to the dimensions of the inducer and its lift-off from the metal surface, and to the position of the sensor. The inducer and the sensor are usually built in one unit, moving together as the probe scans the work-piece [3]. The SMFM technique also offers the possibility of an easy inversion of the crack signal. For this purpose, an inversion curve relating the crack depth to the relative magnitude of the signal discontinuity R_m is used;

$$R_m = \frac{V_2 - V_1}{V_1} \tag{2}$$

where V_1 and V_2 are voltages as shown in Fig. 2.

The U-shape inducer mentioned above can also serve as a source for producing the surface electric field for the ACFM method. Of course, the induced field is not uniform with the implication that a modified form of (1) is required for the inversion of the crack signal.

This paper describes the development of a prototype system utilising a probe for the simultaneous application of the ACFM and SMFM techniques for the rapid inspection of mild

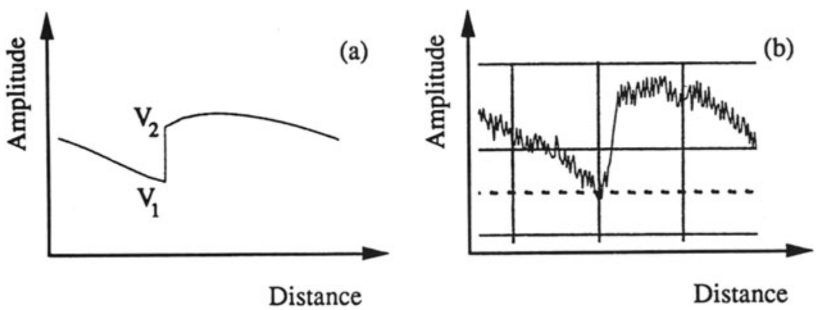


Fig.2 Typical SMFM crack signal; a) Theory, (b) Experiment.

steel structures. The design of the probe, involving a judicious integration of a contacting sensor and a non-contacting sensor as well as the induction mechanism, is presented. Techniques employed for the enhancement of crack signals are explained. Besides an electronic detector, the developed system embraces a real-time signal processor. The signal processing technique is discussed and finally, factors influencing the overall performance of the system are addressed.

THE PROBE

The design technique presented below for the development of the prototype probe is general and can be applied to the design of similar probes with different dimensions.

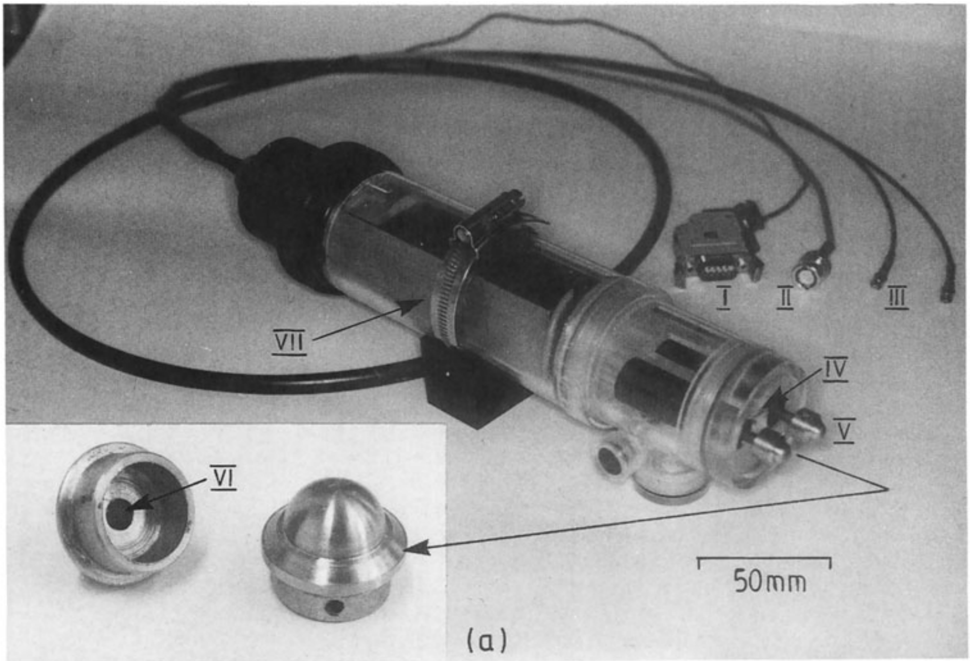
A picture of the prototype probe together with its schematic diagram is shown in Fig. 3. In this probe two parallel U-shaped current-carrying-wires produce the surface electromagnetic field for the ACFM and the eddy-current sensors. The dimensions of the inducer are a = 8 mm, b = 5 mm and l = 70 mm. The last dimension reduces the unwanted induction by the feed-arrangement, ensuring that the field induced in the work-piece is effectively due to the inducer. The choice of b = 5 mm is arbitrary while a = 8 mm was selected commensurate with the criterion for the optimum position of the SMFM sensor in the presence of noise in the detection system [3]. The upper compartment in the probe contains two front-end amplifiers and two optical transmitters. The cable to the probe contains two optical fibres (signal cables), power supply wires, and the field cables delivering to the inducer a 0.5 A ac current at 1.6 kHz. At 1.6 kHz, the skin depth is about 0.3 mm for mild steel which satisfies the condition required for establishing a surface field in the presence of cracks depths of interest (i.e. d > 1 mm). Further reasons for the choice of this operating frequency become evident later. The use of optical fibres prevents interference between the field cable and the signal cables. In the prototype probe, the ACFM sensing legs are stainless steel rods with 2 mm diameter. For smooth traverse over the work-piece, each leg is spring-loaded and has a ball-shape end with a diameter of about 8 mm. Under normal operating conditions, the distance h between the tip of the leg and the inducer is about 10 mm. In the prototype probe, the probe length Δ = 21 mm.

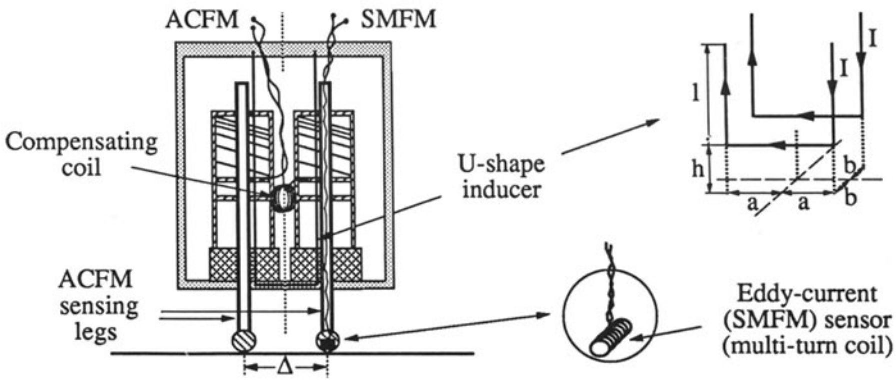
In order to have a fully integrated probe, the eddy-current sensor was encapsulated in one of the ACFM sensing legs, Fig. 3. This arrangement not only gives the sensor some protection against probable damages but it also keeps the sensor at a fixed lift-off distance from the metal surface. As reported in [3], a tape-head eddy-current sensor with a narrow sensing gap and with a small core width is a suitable means for the detection of the surface magnetic field. However, tape-head eddy-current sensors are usually large and cannot be accommodated within the housings provided in the ends of the ACFM probe legs. For this reason, a small coil-type eddy-current sensor was developed. The sensor is a 100-turn coil wound over a 2 mm long optical fibre of 1 mm thickness. The orientation of the coil in its housing is horizontal with respect to the work-piece and its lift-off is about 0.4 mm (which is the thickness of the tip of the housing). Although the eddy-current sensor is fully covered by stainless steel, experiments showed that the enclosure had a little effect on the shape and strength of the crack signal. This can be attributed to two facts; (a) to the nature of mild steel which tends to confine the field to itself and as a result external non-ferrous objects cannot significantly disturb the field at the close vicinity of mild steel and (b) to the weak screening effect of stainless steel housing at 1.6 kHz, allowing a good coupling between the sensor and the surface field.

For the prototype probe, the curves for the inversion of the ACFM and the SMFM crack signals are shown in Fig. 4. In this figure R_m is given in (2) and

$$R_a = \frac{V_2 - V_1}{V_1} \quad (3)$$

where V_1 and V_2 are defined in (1), Fig. 1. The curves in Fig. 4 were generated using a computer program based on a mathematical modelling reported in [2].





(b)

Fig.3 (a) Prototype SMFM-ACFM probe: I) power supply cable, II) field (current) cable, III)signals cables (optical fibres), IV) U-shape inducer, V) ACFM sensing legs, VI) housing for the eddy-current sensor, and VII) front-end amplifiers; (b) Schematic diagram of the probe.

ANALOGUE DETECTION

In the system developed, the two optical signals received from the ACFM and SMFM sensors are initially converted into electric signals. Each signal is passed through a channel consisting of a band-pass filter and a phase-sensitive-detector (PSD). To obtain a high signal to noise ratio, the PSD in the SMFM channel is set to give the highest output while the PSD in the ACFM channel is set to eliminate the parasitic voltages reported in [4]. Since the probe

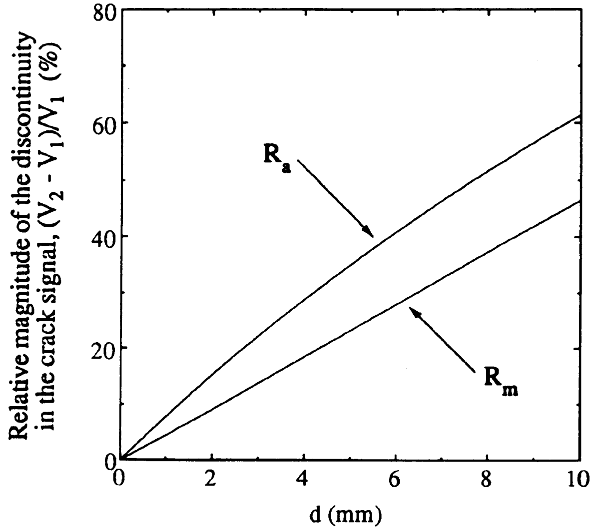


Fig. 4 Inversion curves.

in Fig. 3 has long legs, the probe loop and probe leg parasitic voltages are very strong and therefore give rise to an appreciable ac voltage at the output of the PSD. This effect reduces the resolution of the ACFM technique in crack detection. The effect of these voltages has been virtually removed by introducing a compensating coil within the inducer, Fig. 3, connected in series with the ACFM sensor. The voltage induced in the coil is anti-phase with the parasitic voltage of the probe loop. For the best effect, the position of the coil and its orientation must be determined experimentally. The results of scanning the surface of a mild steel test block containing saw-cut notches of 1 mm and 2 mm depths before and after implementation of the compensating coil are shown in Fig. 5. These results show a marked improvement in the crack signal after the implementation of the coil.

REAL-TIME PROCESSING

A Motorola MC68010 microprocessor-based computer was employed for the real-time processing of the ACFM and SMFM crack signals. An A/D convertor, which is time multiplexed between the two outputs of the two-channel detector converts the analogue signals into digital forms.

The sampling rate of the A/D depends on the speed of scan. If the probe scans the work-piece at a speed of x mm/s and samples are to be taken at every s mm, the A/D convertor should have a sampling frequency of $f_s = 2x/s$ Hz to be able to sample from both channels. Fig 6 shows the reconstruction of the ACFM and SMFM crack signals from their

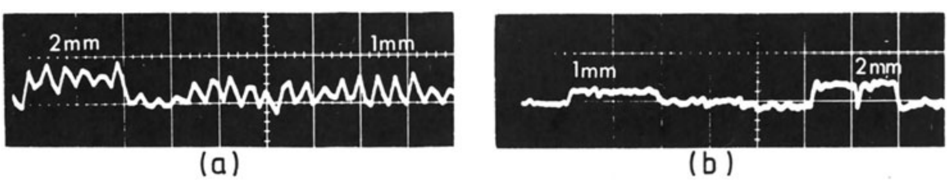


Fig. 5 Effect of the compensating coil on the ACFM crack signal; (a) before implementation, (b) after implementation.

digitised versions when x = 20 mm/sec and f_s= 500 Hz. In the same figure, the theoretical signals are shown for comparison.

Although very fast A/D convertors have now become available, a major problem in the real-time processing of the crack signals lies with the speed of the computer and the efficiency of the algorithm used for the processing of the data. Also, an important factor in the speed of processing is the surface condition of the work-piece which dictates the complexity of the algorithm. For the development of an algorithm for processing the ACFM data, the nature of a crack signal was first studied. A typical crack signal is shown in Fig. 1.b. It contains noise and the signal due to the loss-of-contact. The algorithm developed for the detection of the ACFM crack signal is based on block-by-block data processing. Two blocks of memory of the same size are designated in the computer. While one block of data is under process, the next block is filled up with samples from the A/D convertor. Each block contains data corresponding to a short scanned length. The processing on one block takes place within the time available between samplings for the next block. In the algorithm developed for the crack detection, initially a threshold level which is a percentage of the averaged signal in the absence of crack is generated. The threshold, whose choice depends on the strength of the noise and information on possible crack depths, is fixed after processing the first block. On subsequent blocks, the following check is then applied. The difference between the maximum and the minimum values in a group consisting of 'n' samples is calculated; each block comprised several groups. When the difference exceeds the threshold level, it is an indication that the edge of the crack may have been detected. Following this, a further check is initiated to examine whether all samples in the next group are above the threshold. Should the results of this test be positive, the sample with the minimum value is taken as the lower edge of the crack signal (V_1 in Fig. 1.a). The upper edge (V_2) can then be easily found by establishing which sample has the maximum value. At this point the search stops and the next program which determines the crack size, starts the inversion process using V_1 and V_2. Two points are worth mentioning here. First, a data block should not represent a scan length larger than the probe length, or else the probe may pass the crack while data is still under process. On the other hand, it should not correspond to a short scan length, since the time available may not be sufficient to perform all the necessary checks for the crack detection. The choice of the block size depends on the speed of the computer and the degree of dedication of the computer to the task. Second, the signal due to the loss-of-contact is recognised by a technique based on the fact that this signal falls rapidly towards zero before rising again. In this technique, the difference between the sample with the minimum value and the previous 'm' samples is checked against the threshold. If the result is a negative value, the change in the signal is either due to loss of contact or due to the falling edge of the crack. Both features are immaterial and hence are ignored by the processor. In order to keep the continuity of the search between two successive data blocks, the last m+n samples in the block under process are copied to the top of the block awaiting processing.

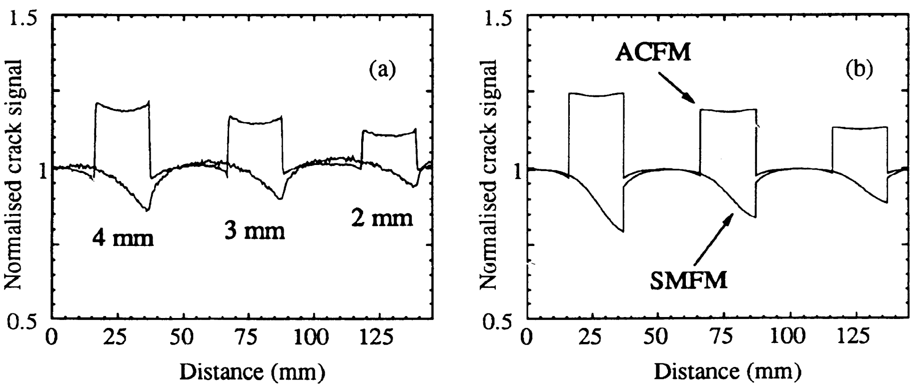


Fig. 6 Typical signals at the output of the detector; (a) Experiment, (b) Theory.

Initial tests showed that the developed signal processing technique works satisfactorily for deep cracks (d > 5 mm). It is found that the inevitable noise in the system (which was predominantly caused by mechanical vibration) is a limiting factor in the detection of shallow cracks. The problem was alleviated by combining an averaging filter with a median filter [5], although such a processing is achieved at the expense of more computing time. The median filter is a powerful tool for suppressing noise without affecting signals with sharp edges. This strategy has extended the resolution of detection to 1 mm deep cracks.

As mentioned earlier, once the crack is detected, the magnitudes of the signal at the crack edge, V_1 and V_2, are accessible. To obtain the crack depth, d, the processor initially computes the value of R_a in (3). This value is then inverted into the depth using a look-up table based on the inversion curve shown in Fig. 4.

Fig. 7 shows an example of the real-time detection and sizing of 4 mm, 3 mm and 2 mm saw-cut notches in a mild steel block as the ACFM part of probe encounters the notches. The numbers 32, 24 and 16 on the computer screen shown in Fig. 7, correspond to 3.2 mm, 2.4 mm and 1.6 mm respectively. In this experiment, the speed of scan x = 5 mm/sec, the sampling rate f = 200 Hz.

For the processing of the SMFM crack signal, Fig. 2, the sudden change in the slope of the crack signal at the crack edge is exploited. A simple algorithm for the real-time detection of cracks by the SMFM technique can be based on this sign change. Initially, a threshold level, V_t, is established using the averaged value (V_r) of the data in the absence of crack. V_t is equivalent to a realistic value of the slope for the discontinuity in the signal for the shallowest crack to be detected. Then, the difference between the averages of two consecutive groups of data is computed and checked against the threshold level. If the difference is less than V_t, the change of the slope is due to the noise. However, should the result be positive and greater than V_t, the last average value can be considered as the lower edge of the crack signal (V_2 in Fig. 2). The upper edge voltage V_1 is approximately equal to the reference voltage (V_r). From values of V_1 and V_2, R_m in (2) is computed. This value is

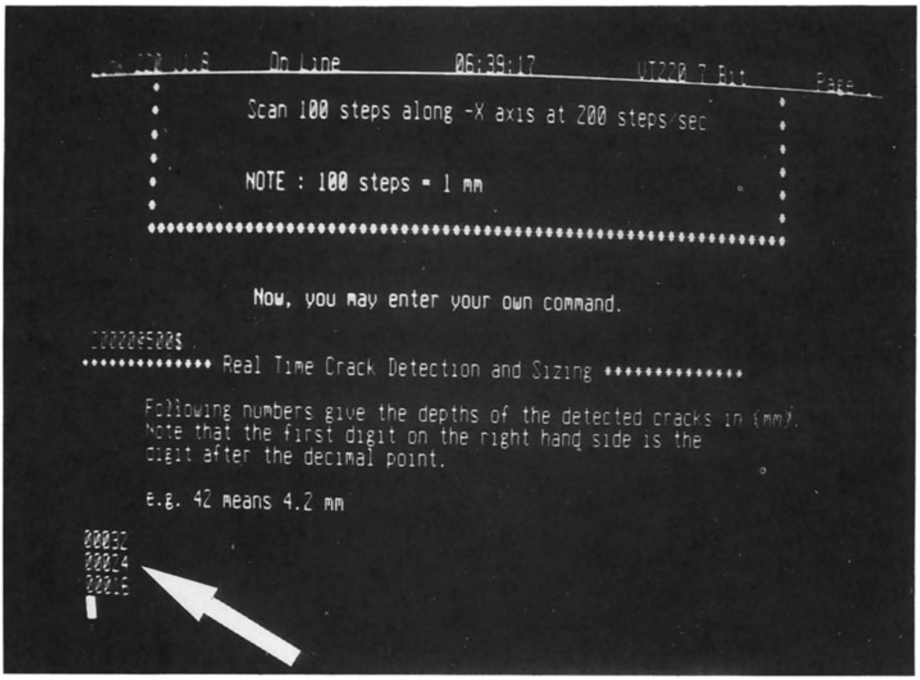


Fig.7 Computer screen after scanning 4 mm, 3 mm and 2 mm saw-cut notches in a mild steel block.

then converted into the crack depth using the inversion curve in Fig. 4. The implementation of the above algorithm is presently under development.

CONCLUSION

The development of an induction probe for the simultaneous measurement of the surface electric and magnetic fields was discussed. This probe picks up the induced surface potential by an ACFM sensor and the induced surface magnetic field by an eddy-current sensor enclosed in one of the ACFM sensing legs. The theory behind the development of the probe was briefly mentioned and techniques for the enhancement of the crack signals were discussed. The main application of the probe is in areas where the ACFM probe may become unreliable due to the loss of contact between the probe legs and the metal surface. The probe is specially useful in those real-time applications where a repeat of inspection may not be possible and undetected cracks cannot be tolerated. A system developed for the real-time analysis of crack signals was discussed and algorithms used for the analysis of the signals were explained. Techniques implemented for the enhancement of crack signals were also addressed. Parts of the system explained are protected by a patent application [6].

The overall performance of the system including the probe was found to be generally satisfactory. However, it suffers from a set of limitations.

(i) If the probe scans a surface with a moderate irregularity such as a well behaved weld, the resulting mechanical noise reduces the detection accuracy of the system.
(ii) The accuracy of inversions depends on the reference voltage fixed by the processor after the first group of data is processed. Therefore the resolution of the system in the crack detection is highly dependent on the reference voltage.
(iii) The system may fail or become inaccurate if the probe encounters a region with multiple cracks.
(iv) The speed of the processor limits the speed of scan. For the processor used, 20 mm/s is the maximum achievable scanning speed.
(v) The shape of the crack affects the inversion accuracy. At present inversions are based on a uniform crack model.

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