SKI Report 2006:26

Research

A Novel Experimental Set-Up for Improving the Sensitivity of SV Waves to Shallow Surface-Breaking Cracks

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March 2006

ISSN 1104-1374
ISRN SKI-R-06/26-SE

SKI perspective

Background

SKI founded this project together with the Rail Safety & Standard Board (RSSB) in UK, to investigate the backscattering of SV waves by surface breaking cracks as a function of incident wave. This is an experimental investigation.

Purpose of the project

The purpose of the project is to find new methods to detect very small surface defects.

SKI has also an interest in building NDE competence at the Royal Institute of technology (KTH) in Stockholm.

Results

The project experimentally shows increasing sensibility for small surface defect using an incident wave close to the critical angle.

Project information

Responsible for the project at SKI has been Peter Merck.
SKI reference: 14.43 - 200443111

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Summary

Conventional inspection procedures to detect surface-breaking defects in train axels and thick pipes often employ 45-degree incidence shear vertical (SV) waves as probing tool. Recently obtained theoretical and experimental results indicate that this method is considerably less sensitivity to shallow surface-breaking defects, than the one in which the angle of incidence is selected to be close to the critical angle of the longitudinal wave. This project has confirmed this thesis by experimentally investigating the backscattering of SV waves by surface-breaking cracks as a function of the angle of incidence. To this end, three cracks of depth approximately equal to 0.3 mm, 0.5 mm and 0.7 were introduced on the surface of steel samples with a thickness of 47 mm. These cracks were insonified with transducers operating at 2.25 MHz, 3.5 MHz, and 5 MHz, which correspond to wavelengths in steel of 1.38 mm, 0.88 mm, and 0.62 mm, respectively. The increase in sensitivity has been assessed in the order of 15 dB.

Sammanfattning

Konventionella provningsprocedurer för detektering av ytbrytande sprickor i tex. tåg axlar använder ofta ultraljudssökare av 45 graders SV typ. KTH har i sin forskning funnit att denna metod är mindre känslig för mycket grunda defekter än om infallande vinkeln väljs i närheten av kritiska vinkeln för longitudinella vågen. Detta projekt undersöker detta experimentellt. Tre sprickor har använts i experimenten med ungefärligt djup på 0.3 mm, 0.5 mm och 0.7 mm i ett provföremål med en tjocklek av 47 mm. I experimenten användes sökare med frekvensen 2.25 MHz, 3.5 MHz och 5 MHz vilket motsvarar en våglängd på 1.38 mm, 0.88 mm och 0.62 mm. Experimenten har uppskattat att känsligheten kan öka i storleksordningen 15 dB.

1. Introduction

The current practice to inspect hollow axles and pipes often prescribes the use of shear vertical (SV) waves to detect cracks or other defects on the component's surface opposite to that on which the probe is placed. Nearly always, such waves are generated upon refraction of a longitudinal wave incident on the wedge-axle interface, and propagate within the component in a direction forming an angle of 45 degrees with the surface.

Practitioners motivate the adoption of this method on the fact that, at the angle of incidence of 45 degrees, the acoustic response of a 90 degree corner is larger than that at any other angle. Indeed, in view of the total reflection experienced by a shear wave incident on the stress-free surfaces of a quarter-space, and of the fact that the whole incident beam is intercepted by the corner, simple geometrical considerations are sufficient to explain such a finding [see Pecorari 2005, and references therein]. The implicit assumption behind the use of a corner as a test-bench to optimize the inspection set-up is that the corner provides a physical model of a surface-breaking crack of very large extent, and, thus, of its acoustic properties. However, *the geometric properties of a surface-breaking crack with characteristic dimensions smaller than the ultrasonic beam diameter, and in particular those of a crack that is smaller than the wavelength of the inspecting beam, are rather different from those of a 90 degree corner. It should not come as a surprise, therefore, that also the acoustic response of a small surface-breaking crack differs considerably from that a 90 degree corner reflector.* In fact, as pointed out by a theoretical model developed already in the early 80s points [Mendelsohn *et al.* 1980], the response of a two-dimensional surface-breaking crack insonified by a shear vertical wave, and measured along a direction forming 45 degrees with the plane containing the crack, is maximum for an angle of incidence of about 30 degrees. A later theoretical model [Pecorari, 2001] confirms this prediction also for a configuration similar to that used in the inspection of interest here (back-scattering mode). In addition, the crack's response is found to be minimum when the angle of incidence is equal to 45 degrees.

This project has been set up to validate the theoretical predictions by using simulated surface-breaking cracks inserted in the stress-free surface of steel beams with thickness comparable to those of the walls of train hollows axles and thick pipes found in nuclear power plants.

2. Materials and Methods

2.1 The samples and defects

Two steel beams with dimension of 58x47x460 (WxHxL) mm^3 have been used in this project (see Figure 1). The surfaces on which the cracks were introduced and those scanned by the transducers were machined to remove macroscopic roughness and defects which may affect the detection of the cracks under examination. The phase velocity for longitudinal, V_L, and shear waves, V_T, at 2.25 MHz were measured and found to be equal to 5.875 10^3 ms^{-1} and 3.24 10^3 ms^{-1}, respectively. The critical angle for longitudinal waves is, therefore, $\theta_L = \sin^{-1}\left(V_T/V_L\right) =$ 33.5 degrees. Attenuation in steel was also estimated at the same frequency and found to be $\alpha_L = 0.003$ dB/mm and $\alpha_T = 0.068$ dB/mm for longitudinal and shear waves, respectively. These data are not corrected for the apparent attenuation due to the beam diffraction. In addition, they have been obtained by using transducers which are in direct contact with the sample. Therefore, they do not account for the attenuation of the inspecting (longitudinal) wave inside the wedge.

The cracks were introduced in the stress-free surfaces of the beams by electro-erosion. Three defects with depths, *h*, equal to 0.3 mm, 0.5 mm, and 0.7 mm and with aspect ratio 1:3 were produced. Typical values of the aspect ratio for surface-breaking cracks range between 1 : 3 to 1 : 5. The largest ratio crack-depth to wavelength, h/λ, is therefore of the order of 1. The opening of the cracks at the surface is lower than 0.3 mm. The tool to fabricate the cracks guarantees a tip radius of the order of 50 μm which is one order of magnitude smaller than the shortest shear wavelength used in this investigation and considerably smaller than the defect employed to obtain similar results recently published by this author (Pecorari 2005).

2.2 The experimental set-up

Figure 2 schematically illustrates the experimental set-up. A piezoelectric longitudinal transducer, which is mounted on a variable-angle wedge (by Panametrics), is excited by a pulser-receiver (Panametrics 5072 PR). The system parameters of the latter are: pulse repetition frequency = 2000 Hz, Energy = 4, Damping = 2, Gain = 50 dB, High-Pass Filter =1 MHz, Low-Pass frequency = full band. The pulser-receiver also triggers the oscilloscope (Tektronix TDS-5052) which digitizes and displays the time-domain waveform.

The transducer's is mounted on a search tube connected to two stages (Newport ILS series) which allow the transducer to be displaced in mutually orthogonal directions and in a plane that is parallel to the surface of the sample (see Figure 1 for a partial view). A motion controller (Newport EPS3000) is used to control the position of the transducer. The transducer is placed on the surface opposite the one hosting the crack. The position of the transducer relative to the crack is read on a ruler with an absolute maximum error of 0.5 mm. This error in the position corresponds to an uncertainty in the angle of incidence of the order of at most 1 degree in the range of interest. The angle of incidence of the inspecting SV wave is evaluated as $\theta_{in} = \tan^{-1}(t/\ell)$, where t is the thickness of the beam and ℓ is the position of the transducer.

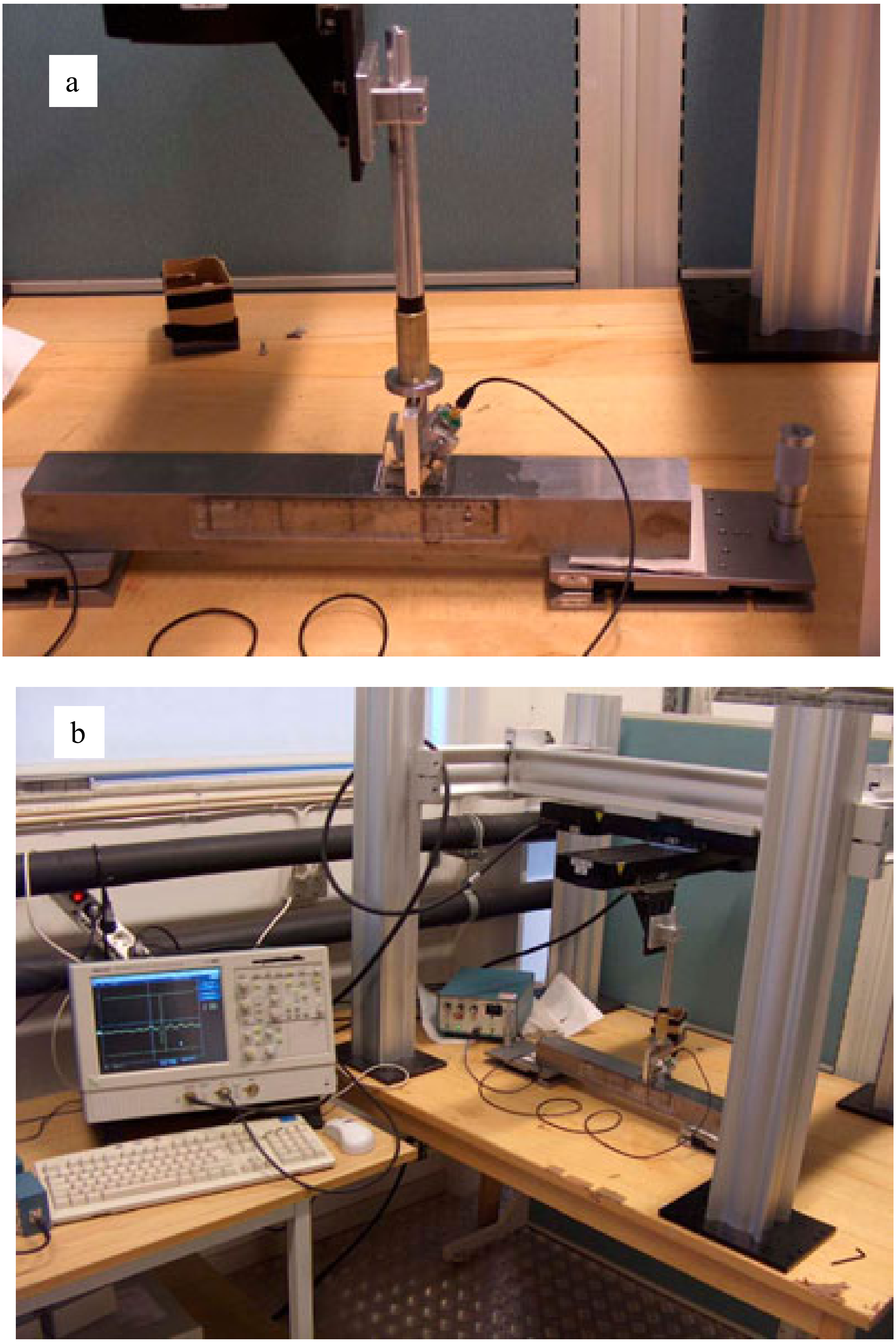

Figure 1: a) detailed view of a steel beam and transducer holder; b) overview of the experimental set up.

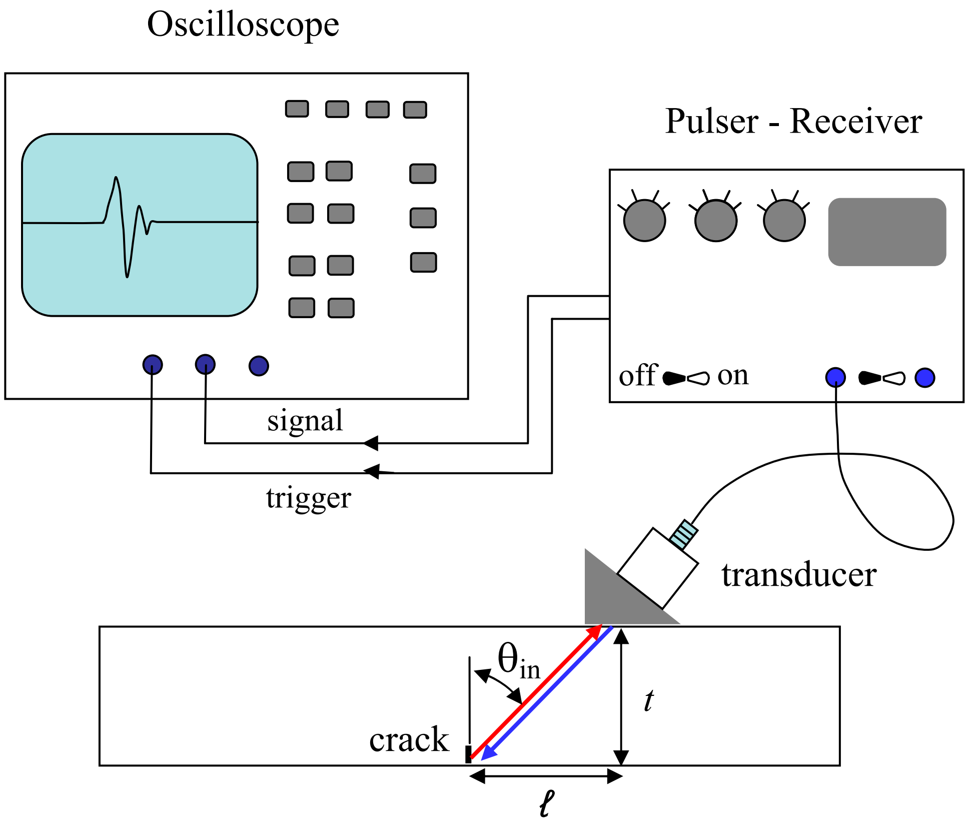

Figure 2: Schematic representation of the experimental set-up

3. Experimental Results

Figures 3-5 report the experimental results gathered in this investigation. Each figure illustrates the dependence on the angle of incidence of the peak-to-peak amplitude of the signal backscattered by a crack of a given depth, at the frequency of the incident wave. The angular domain scanned in each figure is limited by the signal-to-noise ratio. Therefore, in Figure 3a, for instance, the domain is limited between 30 degrees and 42 degrees because at higher angles of incidence the signal scattered by the 0.3 mm deep crack inspected by an SV wave at 2.25 MHz is hidden within the noise. On the other hand, in Figure 5b, which refers to the results relative to the 0.7 mm deep crack insonified by an SV wave at 3.5 MHz, the useful range of angles of incidence goes from 25 degrees to 55 degrees.

Each figure contains four series of data, two of each (black symbols) gathered by insonifying the crack under inspection from positive angles of incidence, and remaining two (white symbols) from negative angles of incidence. This procedure has been adopted to account for possible effects caused by the plane of the crack not being normal to the sample surface.

The three main conclusions to be drawn from these results are:

1. The the maximum backscattered signal is found at angles of incidence between 37 and 40 degrees (see also Fig. 6 and Table I), that is to say, well below 45 degrees.

2. The results of Table I and Figure 6 confirm the theoretical prediction according to which the angle of incidence corresponding to the maximum backscattered signal recorded increases with the depth of the crack from values just above the critical angle for longitudinal waves to 45 degrees.

The magnitude of this effect is partly compensated by the increased attenuation with frequency and length of the acoustic path.

3. Finally, the amplitude of the signal at 45 degrees in all figures is at least a factor of five, i.e., not less than 15 dB, lower than the maximum backscattered signal.

This result proves the superior sensitivity of the proposed configuration to shallow surface breaking cracks

4. Conclusions

This investigation has confirmed experimentally that the sensitivity of SV wave to shallow surface-breaking cracks in thick steel components is not attained at 45 degree incidence, but at lower angles – specifically, between 37 and 40 degrees for the material and crack geometry utilized in the present work. These angles exceed the critical angle of longitudinal waves depending on the crack-depth to wavelength ratio. The increase of **Error! Hyperlink reference not valid.**sensitivity is of the order of 15 dB.

In conclusion, inspections of thick steel components aiming at detecting shallow surface-breaking cracks on the surface opposite that supporting the transducer, should be carried out using wedges which are designed to implement the finding of this investigation.

5. Acknowledgments

The author would like to thank the Swedish Nuclear Power Inspectorate (SKI) and the Rail Safety & Standards Board (RSSB, UK) for providing the financial means to carry out this work

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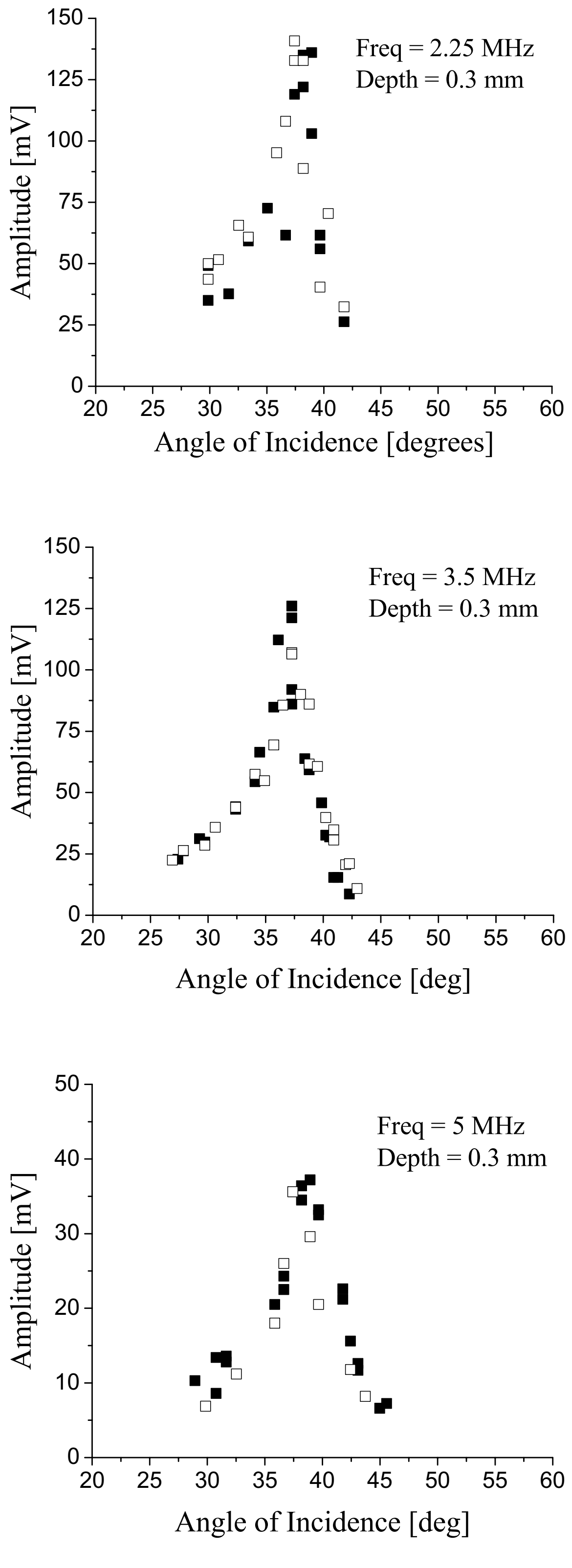

Figure 3: Amplitude of the back-scattered SV waves from a crack 0.3 mm deep versus angle of incidence: a) frequency = 2.25 MHz, b) frequency = 3.5 MHz, c) frequency = 5 MHz.

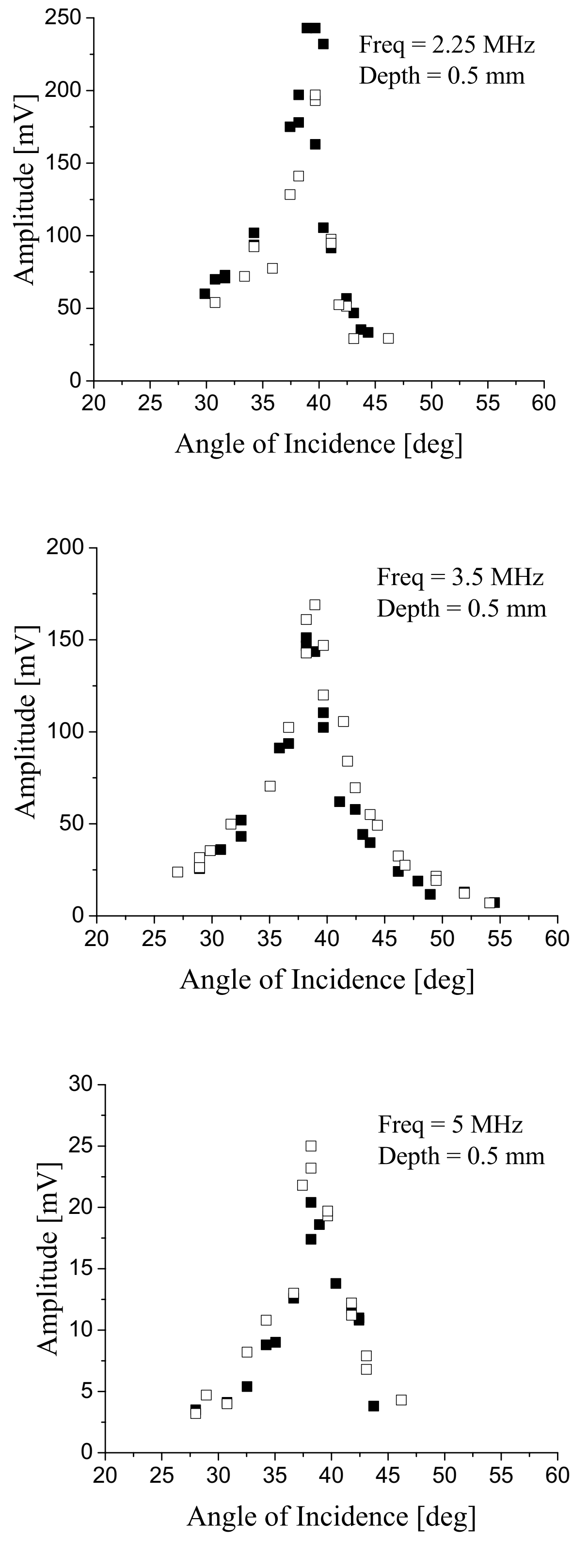

Figure 4: Amplitude of the back-scattered SV waves from a crack 0.5 mm deep versus angle of incidence: a) frequency = 2.25 MHz, b) frequency = 3.5 MHz, c) frequency = 5 MHz.

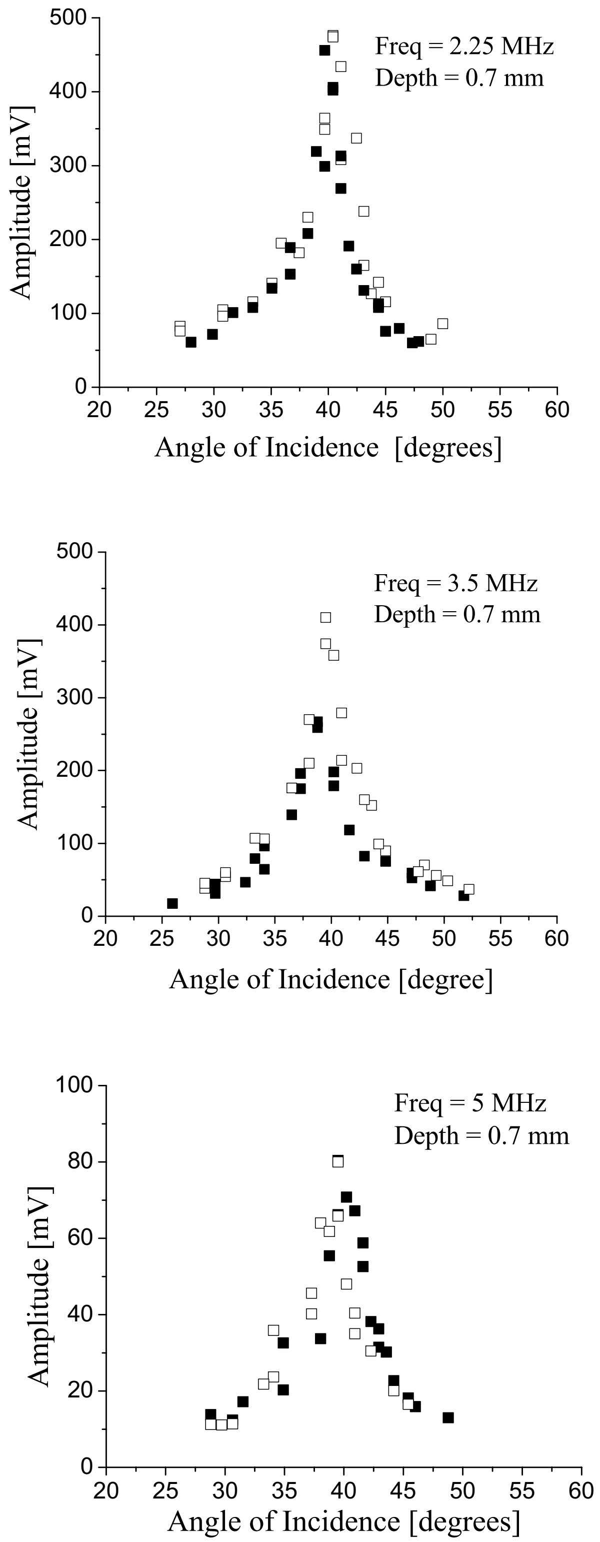

Figure 5: Amplitude of the back-scattered SV waves from a crack 0.7 mm deep versus angle of incidence: a) frequency = 2.25 MHz, b) frequency = 3.5 MHz, c) frequency = 5 MHz.

Table I: Angle of incidence at which the maximum signal was recorded; the first column reports the crack depth and the first row the frequency of the incident wave.

	2.25 MHz	3.5 MHz	5 MHz
0.3 mm	38 deg	37.3 deg	38.2 deg
0.5 mm	39.5 deg	38.4 deg	38.8 deg
0.7 mm	40.2 deg	39.1 deg	39.7 deg

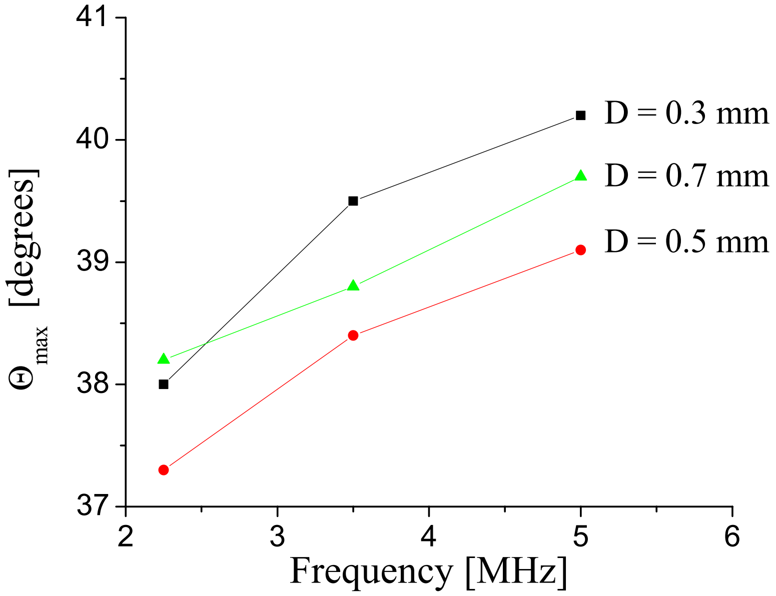

Figure 6. Angle of incidence at which the maximum backscattered signal is recorded versus the frequency of the incident wave for the three cracks examined in this work. The data in this figure are those reported also in Table I.