

THE EVALUATION OF NDT TECHNIQUES FOR ABRASIVE WHEELS

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A study into the techniques available for the non-destructive testing of abrasive wheels was carried out for the Health and Safety Executive. These included X-radiographic, ultrasonic and resonance techniques. A series of fracture studies was also carried out to estimate the typical critical crack sizes for abrasive wheels in use and the results used as an aid to assessing the applicability of each technique. An ultrasonic pitch-catch technique was developed which can achieve the required resolution and is readily adaptable to practical situations. However, in the opinion of the manufacturers and users of abrasive wheels the current practice during manufacture and recommended operating procedures for use are sufficient to ensure the integrity of such wheels.

1. Introduction

The work reported in this paper deals with the assessment of non-destructive testing (NDT) techniques for abrasive wheels. The Health and Safety Executive had indicated that there may be a general requirement for improved practical techniques for assessment of the fitness-for-purpose of abrasive wheels of various types. In particular the location and estimation of the severity of flaws (cracks) in abrasive wheels was of principal importance. When considering various NDT techniques for application to abrasive wheels a number of criteria was used to assess their potential. The basic requirement would be for a technique which can locate and measure defects (mainly cracks) in wheels of a wide range of types, sizes, materials etc. The required apparatus must be robust, simple to use and relatively inexpensive and ideally should be usable both on new wheels and wheels "in-situ".

2. Survey of Current Practice

At the present time there appear to be two tests which are used in the abrasive wheel industry. The resonance test, either by simple listening or the use of the "Grindosonic" instrument, is used to evaluate soundness and/or grade of a particular wheel. The overspeed test is also extensively used, in the first instance to derive the safe operating speed (half the average burst speed) and secondly to assess the fitness-for-purpose of individual wheels (overspeed to 1.5 times the recommended operating speed). It should be noted that a $\times 1.5$ overspeed test represents a stress of 2.25 times the recommended operating stress (Equation 2). Fracture studies (McLaren et al (1978)) have shown this criterion to be highly conservative.

During manufacture, experience and visual inspection are the primary source of quality control and manufacturing defects are not considered to be a serious problem. The current situation was recently reviewed by Haywood (1984).

When the wheels are in use there are a number of mechanisms which can lead to defects either forming or growing in the wheel, although strict adherence to the operating procedures and good maintenance minimise these problems. Any inspection device would be expected to provide a quick check, preferably in-situ, that the wheel is fit for use.

3. Survey of Previous NDT Work on Abrasive Wheels

An initial survey carried out on the National NDT Centre Information Computer Database produced very few references to abrasive wheels. A paper by Niemi and Gröhn (1980) assesses the application of resonance techniques for the grading and soundness of grinding wheels. This approach will be discussed in more detail later.

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References to ultrasonic techniques refer mainly to the use of low frequency transit-time measurements as described by Dickson (1978) and Downer (1976). These techniques rely on the fact that a crack present in the wheel will obstruct the ultrasonic path and hence delay the arrival of an ultrasonic pulse at the receiver. These techniques require measurements to be made at a number of positions on the flat face of the wheel and hence have a number of practical disadvantages (ie the wheel requires dismantling, it is time consuming, and requires operator interpretation) and are not very sensitive to radial cracks at the bore of the wheel.

Dronfeld and Cai (1984) have described the use of acoustic emission to investigate the loading of grinding wheels and for process monitoring. The complexity of the data interpretation would make application extremely difficult other than in research environments.

Many of these techniques are sensitive to the formulation of the abrasive wheel material and as a very large number, many thousands, of such formulations exist they impose severe limitations on any such techniques.

4. Techniques Evaluated in the Present Study

In the present study the aim has been to identify and evaluate techniques which could be developed into a practical inspection tool for the manufacturer, or the user, of abrasive wheels. For this reason a number of techniques has not been considered in any great detail. Examples of such techniques are holographic interferometry, acoustic emission and ultrasonic microscopy. These all may be able to give information on the state of a wheel in an experimental study but would be unlikely to be able to deal with large numbers of wheels quickly and in an industrial environment. Electrical and magnetic testing methods are not applicable. The following sections present the experimental work carried out during this study.

4.1 Fracture Studies

To evaluate the effectiveness of any NDT technique it is necessary to have some knowledge of the scale of defects that affect the fracture properties of the material and hence the sensitivity required. This information was not found in the literature and also did not appear to be "common knowledge". To derive this information, a number of samples suitable for three-point bend testing were produced. The start material was of two different grades from two different manufacturers and was cold-pressed in a metal die to produce bars of 152 mm \times 25 mm \times 18 mm. The samples were then sintered using thermal cycles suggested by the manufacturers. Fifty bars of each batch were produced, of which forty were machined to give 10 samples each containing 10, 5, 2, 1 mm deep \times 1 mm wide notches in the centres of the bars. The bend strengths were then measured at room temperature using a three-point bend test machine with a cross-head speed of 0.5 mm min⁻¹.

The results of these measurements are shown in Fig. 1. The apparent rise in fracture toughness (K_{IC}) up to 5 mm notch depth is due to the geometry of the specimens and inaccuracy in the estimation of small notch depths. In Fig. 1 the mean fracture toughness, with its standard error, is shown, as well as the maximum and minimum values recorded. It can be seen that

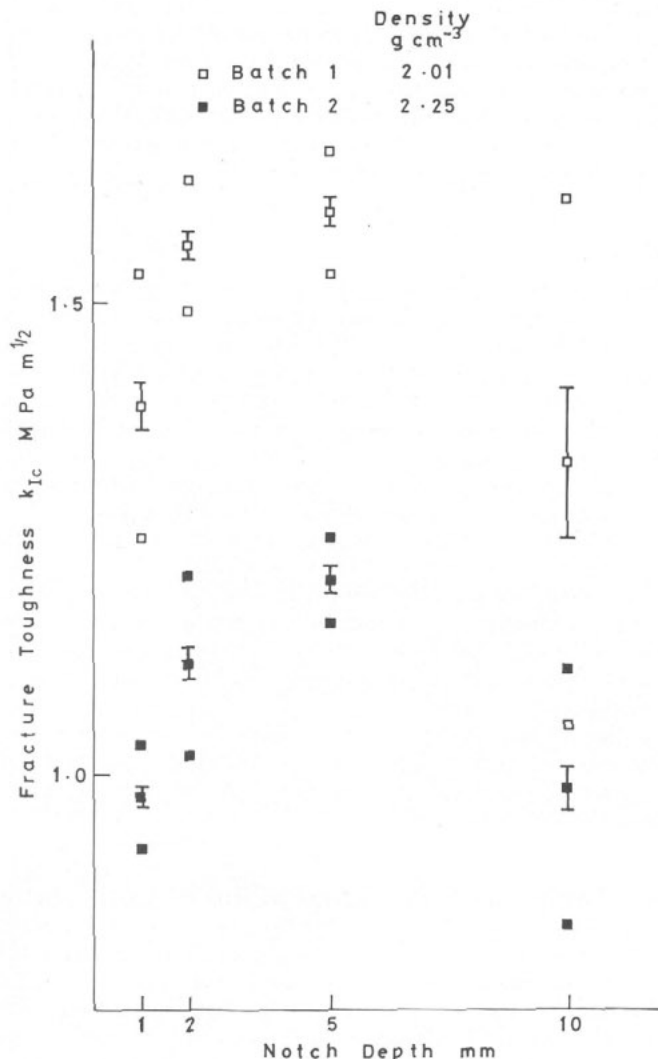


Fig. 1
Fracture toughness values for the notched bars.

the mean fracture toughness does not vary widely with notch depth but that the scatter in the data increases with notch depth. To estimate critical crack sizes we can use this data in conjunction with the operating speed. The critical crack length, a , is related to the fracture toughness by

$$K_{IC} = Y \sigma \sqrt{a} \quad (1)$$

where Y is a constant (~ 2) and σ is the operating stress. For a rotating grinding wheel the stress at the bore can be approximated by

$$\sigma = 2000 V^2 [1 + 0.2 (R_i/R_o)^2] \quad (2)$$

where V is the peripheral velocity
 R_i is the inner bore radius and
 R_o is the outer radius.

Table 1 gives values of critical crack size (a) for various operating speeds for a R_i/R_o ratio of 0.2, using the equation

$$\sqrt{a} = \frac{K_{IC}}{Y \cdot 2000 V^2 [1 + 0.2 (R_i/R_o)^2]} \quad (3)$$

and an average value of $K_{IC} = 1.25 \text{ MPa } m^{-1/2}$.

The exact values for fracture analysis depend upon the density of the wheel, size, shape, etc but Table 1 gives a guide as to the crack sizes that need to be detected. The critical dependence on $(\text{velocity})^2$ is clear from this table. Typical velocities for plain wheels vary from 30 to 50 ms^{-1} .

Hence, for normal operating conditions, cracks of the order of 10 mm must be readily detectable by any NDT technique developed for grinding wheels. This value may also be derived using the statistical approach of the Weibull Model.

4.2 X-radiography

X-radiography is a common NDT tool which can be used for finding cracks, provided they are suitably orientated to the X-ray beam. It is most sensitive to cracks which run parallel to the X-ray beam and insensitive to lamina type cracks which lie perpendicular to the beam. If it is assumed that we are looking for radial cracks at the wheel bore then radiography would be carried out with the X-ray beam normal to the flat face of the wheel. Examples of such radiographs are given in Figs. 2 and 3. Such radiographs were taken at 40 kV with exposure times varying from 45 seconds to 4 minutes 30 seconds depending on the thickness of the wheel. It can be seen that cracks are clearly defined and features are indicated that are not apparent in visual examination. The sensitivity and resolution of X-radiography is very good, probably defining cracks down to a few millimetres in length (depending upon the grain/pore size of the material).

The use of radio-opaque penetrants to enhance the contrast of cracks on the radiographs has been investigated. In particular a penetrant based on zinc iodide was evaluated. It has been found that 'normal' penetrant action does not occur in the grinding wheels due to the porous nature of the vitrified wheels; the penetrant tends to accumulate in the pores and capillary action holds it away from the cracks. Fig. 4 is a radiograph of the same wheel as that in Fig. 1 doped with penetrant and Fig. 5 similarly that of Fig. 3.

4.3 Resonance Techniques

These techniques depend upon the measurement of the mechanical resonant frequency ("natural modes") of a component, induced by a sharp impact. This technique is already familiar in the abrasive wheel industry where it is primarily used for checking the grades of grinding wheels. The measurement is related to the stiffness of the material (Young's Modulus) which for certain simple geometries can in fact be calculated from the resonant frequency. An instrument that is commonly used for such measurements is the "Grindosonic"* which produces a numerical reading which is related to the resonance frequency. It is also claimed that in some circumstances the "Grindosonic" can be used as a flaw detector, ie will find cracks in wheels. The accuracy of the "Grindosonic" instrument was assessed by comparing the reading given by the instrument with that obtained by applying a Fast Fourier Transform to the same input signal. It was found that the "Grindosonic" was excellent at determining the fundamental frequency, even in quite noisy signals, and produced accurate readings.

The ability of the "Grindosonic" to detect cracks was also tested using both the fracture test bars and a grinding wheel with a sawcut slot. The results are shown in Figs. 6 and 7. The two sets of results are apparently inconsistent but careful consideration of the systems involved shows this not to be the case.

* "Grindosonic" manufactured by J W Lemmens-Elektronika, Belgium.

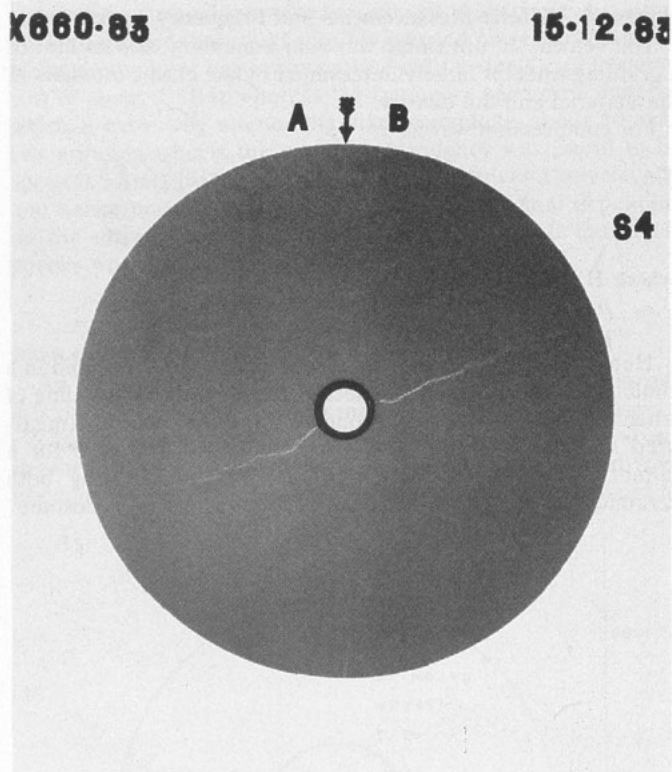


Fig. 2
X-radiograph of wheel S4.

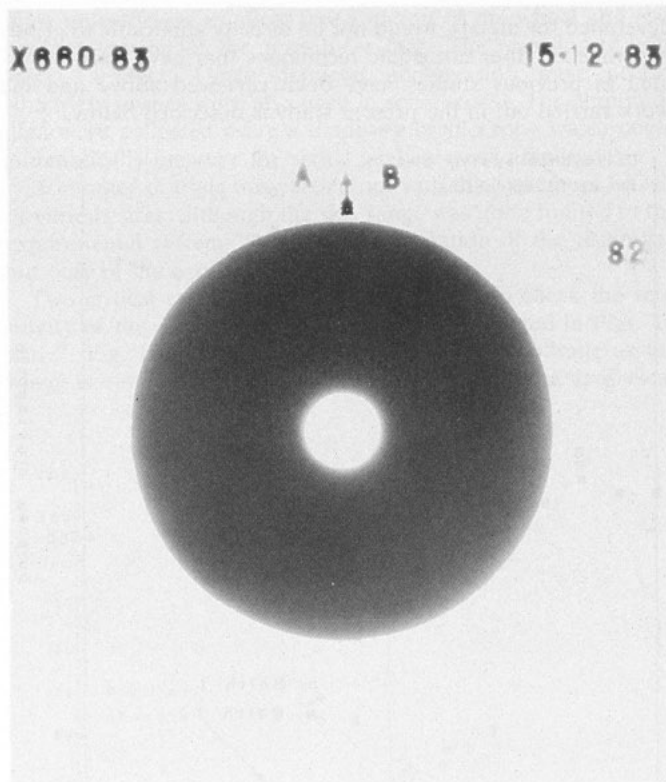


Fig. 3
X-radiograph of wheel S2.

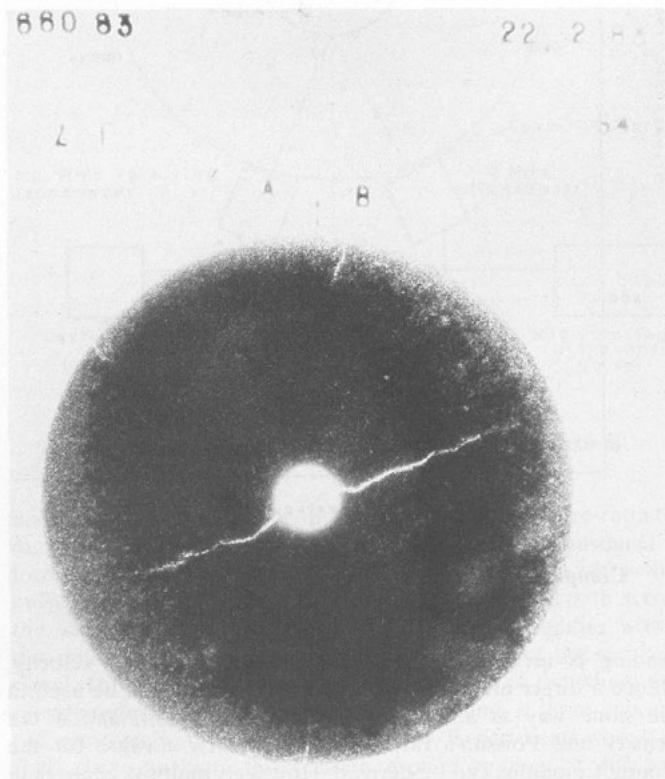


Fig. 4
X-radiograph of wheel S4 with penetrant.

The results from the test bars were obtained by using the "Grindosonic" to its best advantage as the slot is both in the centre of the bar and is an appreciable fraction of the thickness. Hence the stiffness is affected and a change in the "Grindosonic" reading is recorded. In the case of the grinding wheel, the slot is always a small fraction of the radius and the overall stiffness is not appreciably affected and hence there is no change in the "Grindosonic" reading. These results are in

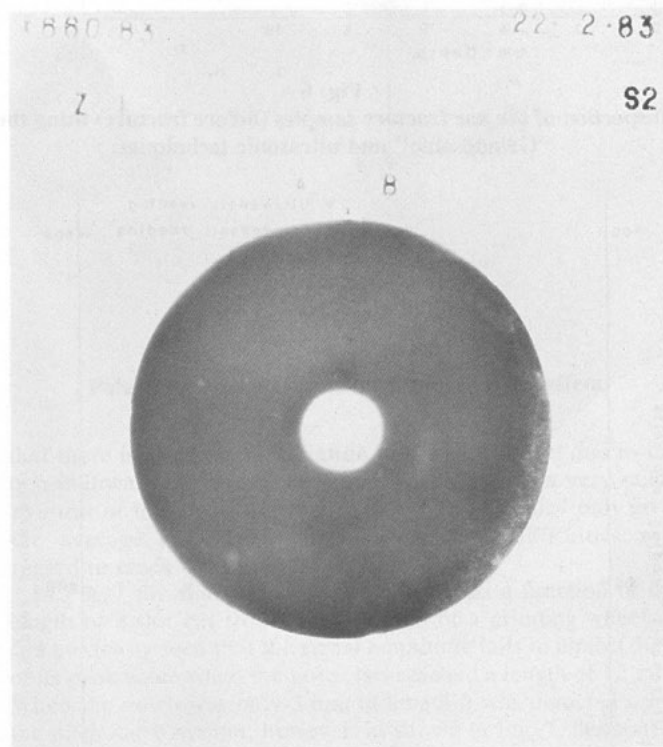


Fig. 5
X-radiograph of wheel S2 with penetrant.

accord with those of Niemi and Gröhn (1980) and indicate that the "Grindosonic" is unlikely to find cracks of the order of 10 mm and less in length in an actual grinding wheel.

4.4 Ultrasonic Techniques

Ultrasound is a standard tool used in NDT and a variety of techniques was evaluated in the present study although it became obvious that the normal "pulse-echo" ultrasonics, as

developed for metals, would not be directly applicable to grinding wheels. Other ultrasonic techniques that have been evaluated in previous studies have been reviewed above and the work carried out in the present study is described below.

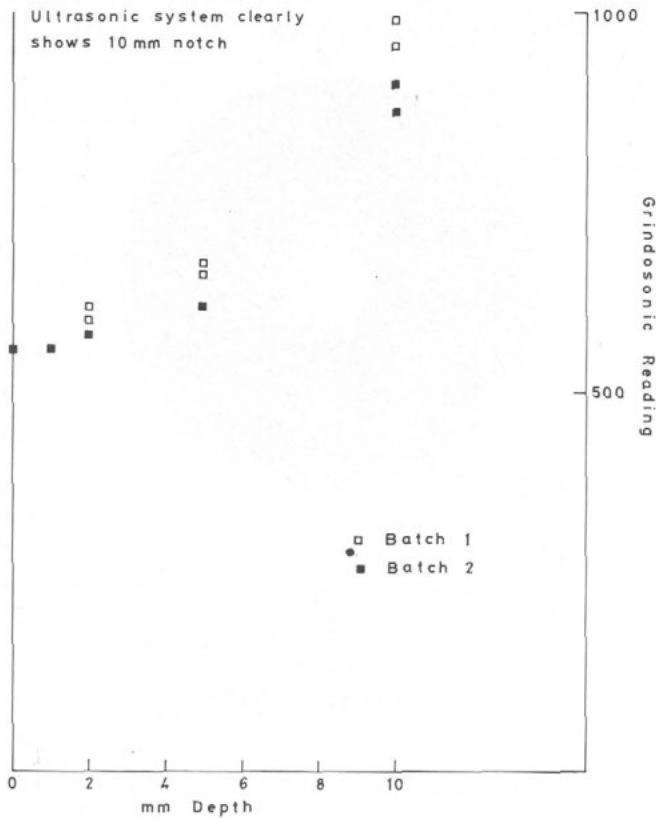


Fig. 6

Inspection of the bar fracture samples (before fracture) using the "Grindosonic" and ultrasonic techniques.

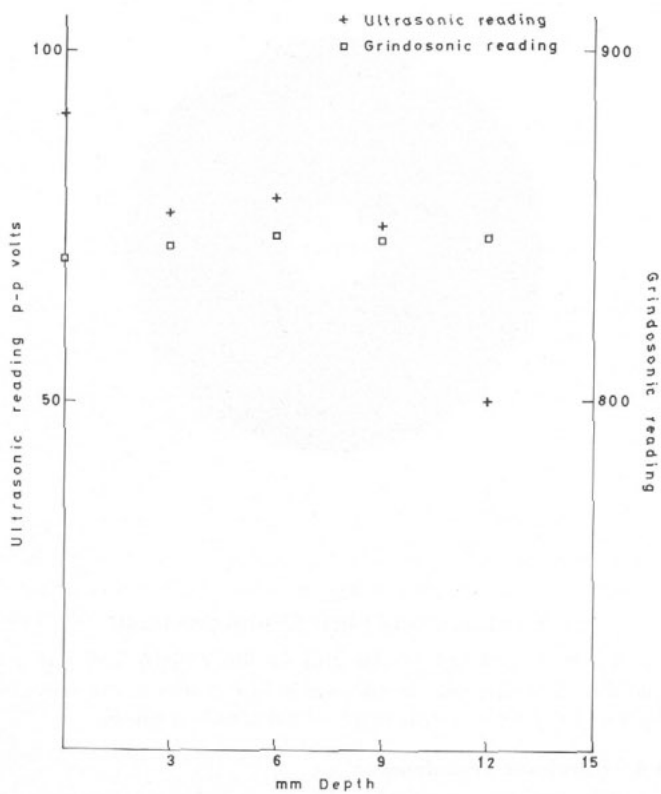


Fig. 7

NDT of grinding wheel with notch in the bore.

Ultrasonic Velocity Measurements and Frequency Analysis

The velocity of ultrasonic waves in a medium such as that of a grinding wheel is largely determined by the elastic modulus of the material and the density.

For compression waves:

$$V = \left[\frac{E}{\rho} \frac{1 - \nu}{(1 + \nu)(1 - 2\nu)} \right]^{1/2}$$

where E is Young's modulus,
 ρ is the density and
 ν is Poisson's ratio.

Hence an ultrasonic velocity measurement could be used in a similar way to the resonance technique to check the grading of wheels. In Fig. 8 the corresponding ultrasonic velocity (measured at 1 MHz) and "Grindosonic" values are plotted for a number of different (good) grinding wheels covering both ceramic and resinoid wheels. As expected, the "Grindosonic"

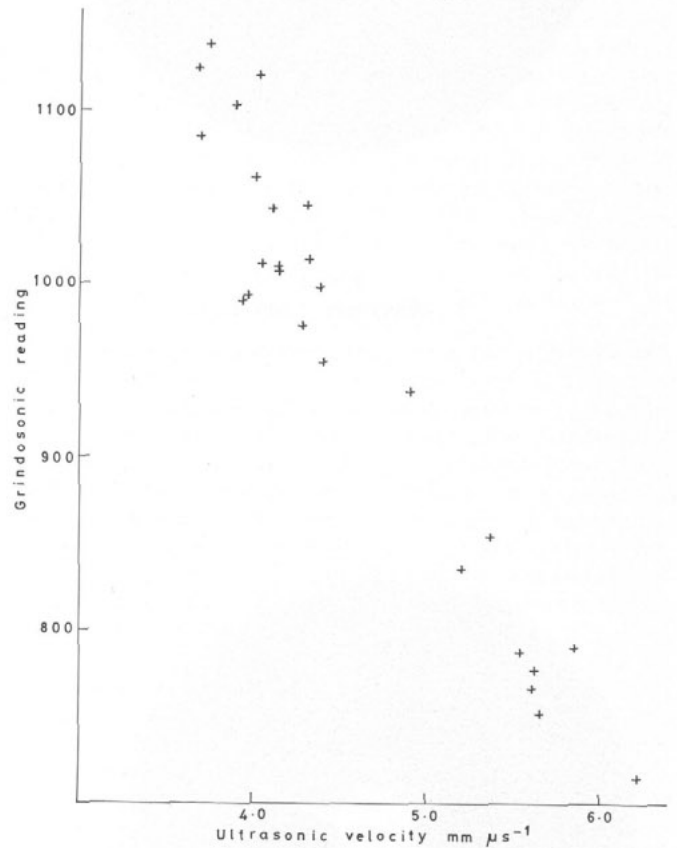


Fig. 8

Comparison of ultrasonic velocity measurements with "Grindosonic" measurements.

reading is inversely proportional to the ultrasonic velocity. Hence a direct ultrasonic velocity measurement can be used in the same way as a "Grindosonic" measurement, and if the density and Poisson's ratio are known then a value for the Young's modulus can be derived. However, multiple changes in the composition and structure of the wheel could confuse the meaning of any reading.

Grinding wheels have a porous structure in general and hence, as pores scatter ultrasound strongly (Sayers and Smith 1982), any ultrasonic wave passing through a wheel is rapidly attenuated. The degree of attenuation is also a function of the frequency of the ultrasound, increasing with the fourth power of the frequency (Rayleigh scattering), but the resolution capability of an ultrasonic measurement also increases with frequency, the maximum resolution being of the order of the wavelength of the ultrasound. Measurements of the ultrasonic

transmission properties were carried out to estimate the maximum frequency that could sensibly be used on grinding wheels. Normal ultrasonic inspection carried out on steels uses frequencies of about 2 MHz whereas the frequency used on a material which is extremely attenuating, like concrete, is about 50 kHz. For grinding wheels the optimum frequency was found to be about 0.5 MHz (500 kHz) to 1 MHz, which gives a wavelength, and hence maximum resolution, of about 4-16 mm depending on the ultrasonic velocity of the particular wheel. Extremely porous wheels may require a lower frequency.

Pitch-Catch Technique

An ultrasonic technique based on the "pitch-catch" principle was developed during the present study; specifically for inspecting grinding wheels. The basic principles of this method are shown in Fig. 9 where an ultrasonic pulse is propagated from the edge of the wheel towards the centre.

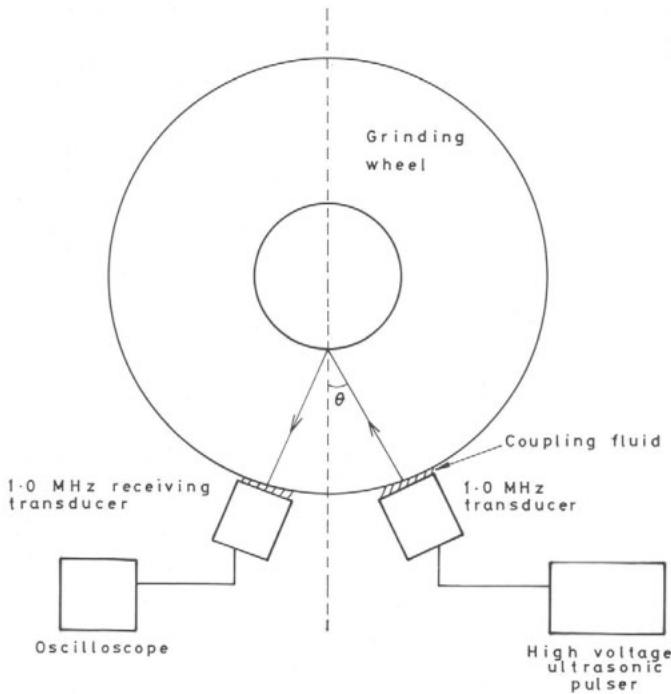


Fig. 9

Schematic of pitch-catch ultrasonic inspection system.

hole is used as a reflector of the ultrasound and it re-radiates the pulse back towards the wheel rim. A second transducer is located on the wheel rim to receive the returning ultrasonic pulse. Hence the pulse itself travels in a "V" shaped path across the wheel. If there are any cracks or inhomogeneities within this path they will cause a change in amplitude of the received signal. In particular, radial cracks at the bore of the wheel will greatly reduce the amplitude of the signal and, if large enough, will completely stop the ultrasonic pulse. Experiments were carried out to evaluate this technique on a number of different grinding wheels.

One of the major problems with this, as with any ultrasonic technique, is that of coupling the transducers to the wheel to allow the propagation of ultrasonic waves from the transducer to the wheel. Initial experiments used a standard coupling gel with the transducers clamped to the edge of the wheel. This system was found to introduce too much variability in the signal from the coupling, and an immersion water-bath was used to provide the coupling with the wheel supported on a spindle to simulate actual mounting conditions. The separation of the transducers and the wheel edge was kept to a minimum but

must be sufficient to allow free rotation of the wheel and also prevent erosion of the transducer face. The transducers used were 1.0 MHz, 1-inch diameter compression wave probes (0.5 MHz probes were also used in some trials). The amplitude data were collected using a digitising oscilloscope which could automatically measure the signal peak-to-peak amplitude.

A number of trials was carried out with this system on wheels of various sizes, although the size range was quite limited in the experimental system. This is not a limitation of the technique but only of the experimental system.

Two critical experiments were carried out to check the sensitivity of the system and the results are illustrated in Figs. 10 and 7. Fig. 10 shows the variation in signal amplitude as the wheel is rotated on the spindle in polar plot form. It is clear

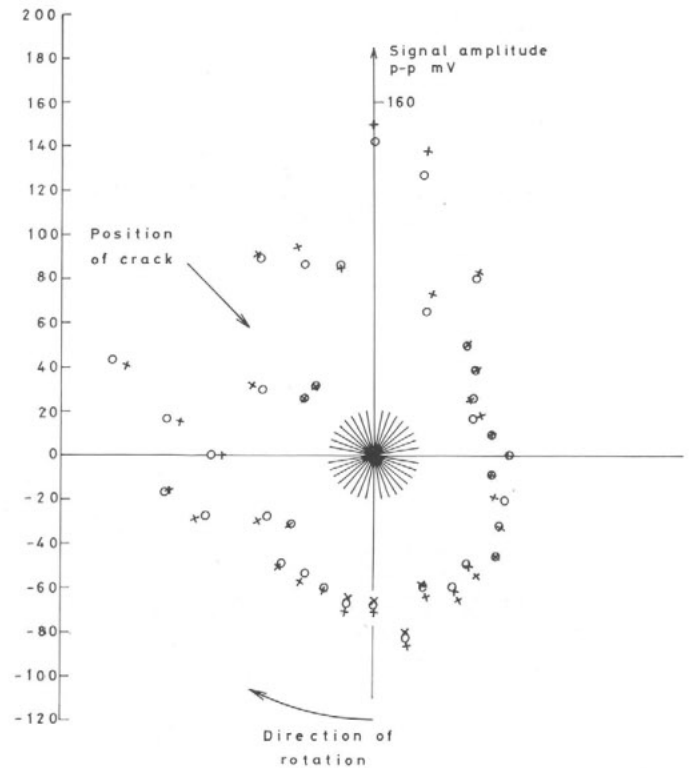


Fig. 10

Polar plot of signal level from pitch-catch system.

that there is an inherent variation in the signal level due to the non-uniform structure of the good wheel. This is a very sensitive test of the wheel uniformity (the "Grindosonic" only gives the average properties) but could lead to difficulties with regard to crack detection.

In Fig. 7 the signal amplitude is plotted as a function of the length of a slot cut from the inner rim of a grinding wheel. It can be clearly seen that the signal amplitude falls to almost 50% of its peak value when the notch has reached a length of 12 mm. When the notch was only 3 mm in length it was detected using the pitch-catch system; however, as shown in Fig. 7, the system did not appear sensitive to the notch increasing in length until it was 12 mm long. (The "Grindosonic" shows no variation in reading.) As critical flaw sizes (Table 1) are around 12 mm for wheels running at their recommended operating speeds, the system would appear to be of value in detecting such flaws.

This system has a number of attractive features for a practical inspection tool for grinding wheels.

- 1 Access is from the outside rim making "in situ" inspection possible.
- 2 It is most sensitive to radial cracks at the inner bore (usually assumed to be the most critical).

- 3 Different geometries (eg varying radii) can be accommodated easily.
- 4 The required data analysis is relatively simple.

Surface Wave Techniques

Over the past few years the National NDT Centre has developed a technique based on surface waves to detect surface opening cracks in concrete (Smith 1984). The technique is shown schematically in Fig. 11. It was expected that this technique could also be applied to grinding wheels. A trial run on a

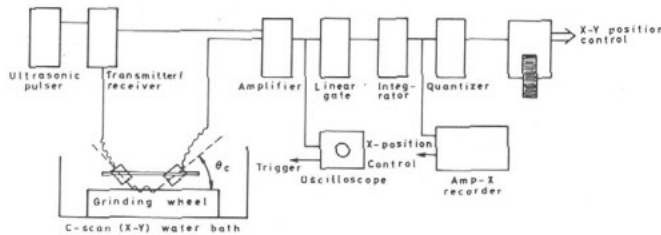


Fig. 11
Schematic diagram of the ultrasonic surface wave scanning system.

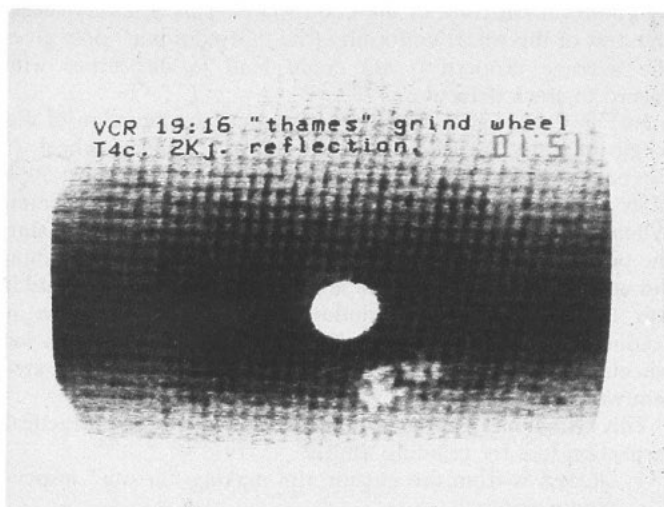
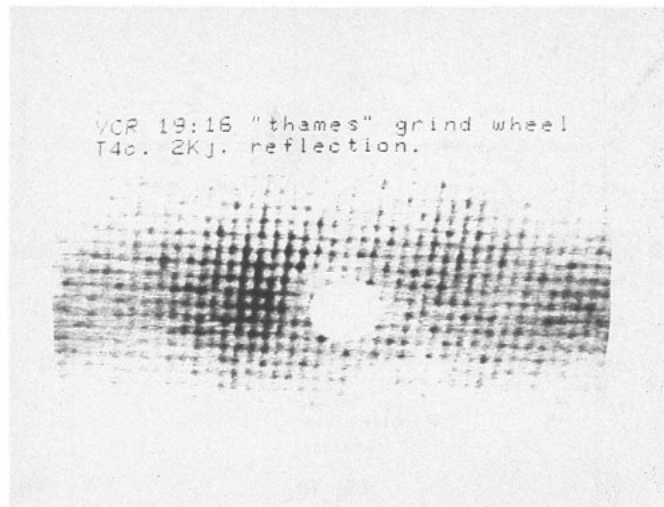


Fig. 12
Thermographs of reinforced cutting-off wheels.

cracked wheel was carried out with the wheel immersed in water and the inspection applied from the flat face. As expected, a loss of signal was observed due to the presence of the crack. This technique could also be used on the outside rim of a wheel but would probably be affected by the state of the surface after use. Scanning both flat faces would be a time-consuming and relatively costly process, hence this technique is not favoured for grinding wheel inspection.

4.5 Pulsed Video Thermography — Cutting-Off Wheels

Most of the techniques discussed above are not suitable for the examination of cutting wheels. The integrity of these laminated cutting wheels, which are usually a few millimetres thick, is very important, due to the very large numbers used. In particular, a technique to inspect the bonding of the reinforcing material to the matrix is required. Pulse video thermography (PVT) has recently been developed at the National NDT Centre for the inspection of composite materials (Reynolds and Wells 1984) and therefore was applied to examples of cutting-off wheels supplied by a manufacturer. The results are shown in Fig. 12 and produce clear images of the reinforcing network. These images are produced in a fraction of a second and recorded on video tape, which can then be replayed frame-by-frame for analysis. It had been hoped to evaluate the technique on some defective wheels, but the availability of suitable specimens did not allow this. However, the results obtained using PVT are sufficient to show its potential as an inspection tool for these cutting wheels.

5. Conclusions

The work presented in this paper has shown that a number of techniques can contribute to the non-destructive testing of abrasive wheels for fitness-for-purpose. Two principal criteria have been used to assess such techniques; their sensitivity to cracks predicted to be of critical size and their suitability for practical use. The most sensitive technique was found to be X-radiography, but it is concluded that it would probably be too expensive and time-consuming for widespread use. The resonance technique, which is widely known in the industry, was also evaluated and found to be effective for grading wheels but not sensitive enough to detect cracks of the critical length. A variety of ultrasonic methods of inspection was investigated and, of these, a system using "pitch-catch" ultrasonic waves was found to have the required sensitivity, coupled with the potential to be a relatively cheap, quick and simple in-situ test. However, this technique would require a programme of development before it could be used in practice.

A special problem considered was that of the inspection of reinforced cutting-off wheels. These wheels are not amenable to the techniques discussed above but a technique using pulse video thermography has been demonstrated to be effective. This system is very fact but is, at present, rather expensive. Further evaluation of cheaper thermographic systems is required.

However, the views of the manufacturers and users of abrasive wheels should also be taken into account when considering these results. As discussed above, the current practice during manufacture and the operating procedures for use, provided they are adhered to, are considered to be sufficient to ensure the safe use of abrasive wheels.

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Table 1
Critical crack sizes for various operating speeds

$$\frac{R_i}{R_o} = 0.2$$

Peripheral Speed ms ⁻¹	Critical Crack Size mm
20	600
30	118
40	38
50	15
60	7
80	2
100	1

References

1. Dickson, J. K. An ultrasonic test method for inspection of carborundum wheels. Balteau Sonatest, August 1978.
2. Dornfeld, D. and Cai, H. G. An investigation of grinding and wheel loading using acoustic emission. Trans. ASME 106, Feb 1984.
3. Downer, R. Materials sounder to detect cracks in grinding wheels. Tooling, June 1976.
4. Haywood, S. A. Mechanical design safety of vitrified grinding wheels. British Ceramic Trans. 83 (5), 1984.
5. McLaren, J. R., Davidge, R. W., Cotton, D. C. L., Haywood, S. A. and Robson, M. E. The mechanical behaviour of vitreous-bonded aluminas under various stress-time schedules. Proc Brit Ceramics Soc 26, 1978.
6. Niemi, M. and Gröhn, S. Non-destructive testing of grinding wheels and optimisation of the grinding. HSE Transl No 10278. 1982.
7. Reynolds, W. N. and Wells, G. M. Video-compatible thermography, Brit J NDT 26 (1) 1984.
8. Sayers, C. M. and Smith, R. L. The propagation of ultrasound in porous media. Ultrasonics Sept 1982.
9. Smith, R. L. The use of surface scanning waves to detect surface opening cracks in concrete. NDT International 17(5) Oct 1984.