THE APPLICATION OF ULTRASOUND AT HIGH TEMPERATURE- A REVIEW.

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ABSTRACT

Ultrasound becomes more relevant in today's industries. This is due to its wide range of application and ability to perform testing without destructing the sample and, without shutting down the plant operation. This paper presents several ultrasound techniques that are suitable for high temperature measurements.

Keywords: Ultrasonic (UT), High temperature transducer

Introduction

There are many Non Destructive Testing (NDT) techniques that can be used at high temperatures such as thermography and ultrasound. However, only the ultrasonic technique will be discussed here due to its wider applications in industries. There are distinct differences between ultrasonic measuring methods that should be applied to various inspection problems.

The processing of materials from the most basic, such as casting of steel, to the most advanced process, such as the epitaxial growth of optical or electronic materials, is undergoing a radical change. Recent scientific advances have greatly improved the understanding of many of the phenomena involved in processing. This in turn, has resulted in the emergence of sophisticated process models capable to predict the effect of process variables, and the microstructure properties of the processed materials (Blitz & Simpson, 1996).

Measurements at high temperatures are becoming more important in the industries; where they have been used for the inspection of the nuclear reactor (Govindaraju et.al. 1997; Hongerholt et.al. 1997), welding pool monitoring (Patel & Nicholson, 1990), steel mill (Wadley et. al., 1986, Xia et. al., 1991) and thermal wave generation (Wadley et.al. 1986).

Ultrasound is the name given to the study and application of the ultrasound, with frequencies greater than about 20 kHz. Ultrasonic waves have a wide variety of applications including cutting, cleaning and the destructive of tissue at the upper extremity and non-destructive testing (NDT) at the lower end. A non-destructive test is a technique where no impairment of the properties and performance in future uses of the object under examination. It is essential that there have been no changes in the dimensions and structures of the object after test. The ultrasonic testing can be performed by propagating low ultrasonic waves through a material and the results can be interpreted either in the time of travel or any change of intensity for a given distance. Applications include thickness measurement, flaw detection and measuring parameters (such as elastic moduli and grain size), which are related to the material structures. There are several advantages using ultrasonic as opposed to audible frequencies and they are:-

a. Wavelengths decrease inversely with frequency, eg; $c = f\lambda$. This is an advantage when testing small samples having dimensions of the same order of magnitude as the wavelength used. The use of shorter wavelengths enables the employment of shorter pulses, thus providing higher degrees of resolution for defect detection.

   Furthermore, the degree of beam spread decreases with an increase in frequency and, hence, an increase in directivity; this is of great importance for locating defects.

b. Attenuation generally increases with frequency with the result that the degree of attenuation, which is often related to material structures, can be more easily detected and measured.

The advantages of using the ultrasonic testing are:

a. Testing can be carried out from a single surface.
b. A high degree of penetration is possible in many commonly used materials, which is in contrast with the lower degree of penetration encountered with radiological testing of metals.
c. The accuracy in locating and measuring defects.
d. The ability to detect and size very small defects.
e. The compatibility with automatic scanning devices and with microprocessors and computers (Blitz and Simpson, 1996).

The original "multiple echo" method can be easily applied to material testing with one side access. Figure 1 shows what happens when an ultrasonic search unit is applied. Transducer A in Figure 1 shows a high frequency transmitter which converts the electrical signal to a mechanical vibration by a piezoelectric element within the probe. The use of liquid couplant allows the mechanical vibration, known as longitudinal wave to enter the material. The vibration precedes the material through the sound velocity c_l. After a time T, the captured signal is developed. Due to the reflection factor at this interface, the direction of the wave propagation is reversed; the sound waves are reflected, as shown by transducer B. After reaching the original surface again, part of the pulse is received by the probe and reconverted into an electrical pulse which is displayed on the CRT of the ultrasonic instrument as an "echo", at a distance proportional to the time required to travel the path length s, which is twice "t" the thickness. Not all pulse energy is converted, but, due to the reflection factor at the metal/coupling agent interface, some energy is redirected and passed the previous distance for a second time or a third time, and so on until all energy is finally received, as shown by transducers C to H. Consequently the multiple echo patterns are displayed.

From this phenomenon, velocity and thickness of the material can be calculated, non-destructively, if either one of these parameters, is known, as explained from the following simple equation:

$$\{\text{Velocity}\}_{\text{material}} = \left\{\frac{2 \times \text{Distance(thickess)}}{\text{time}}\right\}_{\text{material}}$$

The time of flight in a material may vary with the change of temperature. This is further described by Wadley et. al. (1986) in his paper. In general, the relationship of the time of flight at position y_m and time t_m is given by;

$$\tau(y,t) = \int_{-a}^{a} \frac{dx}{v_o + \beta \hat{f}(x,t)\hat{f}(y,t)},$$

where v_o and β are known constants. The percentage of change is different for different materials. Since the sound velocity changes to a lower value, the reading will be towards greater thickness. The lower the basic sound velocity at ambient temperatures, the greater the difference usually becomes. The heat conductivity of the material must also be considered. For example, if a hot gas at 500°C flows inside a pipe and the outside temperature is 350°C, then within the wall there is a gradient of 150 degrees, and therefore a measurement will be characterized by some average sound velocity. The heat distribution will be very different (and therefore the average temperature) if at a different point of the same tube only 250°C is measured at the outside surface. In calculating the achievable accuracy, it is therefore advisable to use the worst-case condition. Here, computation based on the highest temperature should be used to remain on the safe side for the wall thickness reading (Walter, 1974). The relationship of the ultrasonic velocity and the temperature for AISI 304 stainless steel and AISI 1018 carbon steel are shown in Figures 2 and 3.

Transducers For High Temperature Measurements

The ceramic components are often used at high temperatures and it is therefore important to monitor high temperature performance *in situ*. High temperature transducers are usually made from ZnO, $LiNbO_3$, LMN composites and PVDF piezoelectric materials (Patel and Nicholson, 1990). The dielectric properties of aluminium nitride (AIN) films and their applications to high temperature as a sound generating devices are discussed by Patel (1990). The AIN has many potential applications; such as the high frequency submerged arc-welding (SAW) devices, optical devices operating in the UV region and high temperature conductivity substrates for integrated circuit, etc. It has attractive properties which are (Patel and Nicholson, 1990):

a. high dielectric strength ($>2 \times 10^7$ V/cm),
b. low relative dielectric constant (8.6),
c. high thermal conductivity (~200Wm/K),
d. high electrical resistivity ($>10^{11}\,\Omega$ cm),
e. wide band-gap (~6.2 eV),
f. stability at high temperatures,
g. high sound velocity (~10 700m/s) with thickness coupling coefficient (k_t) of ~20%.

The high sound velocity makes AIN an attractive material for upper-GHz ultrasonic devices. There are two ways of producing the transducer for this purpose. Firstly it involves careful lapping of bulk piezoelectric and secondly, the deposition of films on suitable substrates. The first technique uses a piezoelectric disc which is bonded to a suitable material acting as backing or delay rod. The second method involves deposition of the piezoelectric as a film on suitable substrates by reactive sputtering or CVD processes. AIN films can be obtained by both methods (Patel and Nicholson, 1990). This paper will not discuss in detail on the piezo materials and structure.

Stubbs et.al. (1996) developed and tested a sensor that is capable of emitting and receiving ultrasonic energy at temperatures exceeding 900°C and pressures above 150 MPa. The sensor works with standard ultrasonic pulser- receivers and has demonstrated the capability of measuring work piece deformation during hot isostatic pressing. Furthermore, due to the nature of the piezoelectric properties of the AlN film, it is expected that the film can be used at temperatures exceeding 1200°C. The current design for the entire sensor also should allow its use at temperatures approaching 1200°C. In addition for the usage as a displacement sensor, Stubbs et.al. (1996) investigates the sensor's application to defect detection, material characterization, and mechanical properties measurements at elevated temperatures.

The Application At High Temperatures

1. On Line Weld Pool Monitoring And Defect Detection

The application of sensing techniques such as optics and ultrasonic to monitor and control the welding process has become an important area of research in recent years. However, the use of the ultrasonic sensors to detect defects as they form in the interior of the weld pool whilst welding is in progress has received less attention, especially when applied to realistic industrial welding situations.

The experiment which uses ultrasound for this purpose has been done by Stares (1990). His experiment employed a stationary welding torch and a moving work piece. The welding parameters include currents from 80 A to 135 A, voltages from 11 V to 13 V and travel speed of 1.7 mm/s. The wire feed speed was chosen depending on the quality of weld but varied from 1.3 mm/s to 4 mm/s. The welding gas used was argon with 2% hydrogen for austenitic stainless steel grade 321, and argon for ferritic steel, BS4360 grade 43A.

The transducers were placed on either side of the welding head. As a transmitter, a 10 MHz 70° angled compression probe and a 4 MHz 60° shear probe (pulse echo) were used on one side and a 10 MHz 70° angled compression probe on the other side to act as the receiver for transmitted compression waves. The divergence couple of the transducers was approximately 10°. The distance between the transmitter and the receiver was kept constant at 74 mm. In all welding trials, the transducers were moved with the welding head and acted as an on-line weld monitor. The contact between the transducer interface and weld was a water irrigator system.

A linear encoder was mounted on the side of the welder, and ultrasonic data were acquired during welding at 1 mm intervals as the welding electrode moved along the weld preparation. The data were recorded by using a Harwell Zipscan^{TM}. This digital instrument provides rapid signal averaging, analysis, display and permanent recording of the un-rectified data using a 21 MHz transient recorder and an LSI11 microcomputer. The system also controls the firing sequence of the transducer. A schematic diagram in Figure 4 shows the arrangement of the ultrasonic probes which were used to monitor root-pass welds; S is the pulse-echo shear probe, T/R is pulse-echo probe (compression) and R is transmission receiver probe (compression). The ultrasonic B-scan data obtained from the machined specimen is shown in Figure 5. The detail of this experiment is described in Stares et.al, 1990. Stares et.al. reported that the lateral width of the weld pool can be measured (estimated error ± 0.8 mm) together with any changes in its dimensions due to external disturbances by means of transmitted compression waves. Pulse-echo ultrasound was less sensitive to changes in weld pool size for the geometry of these experiments. The same probe array can be used simultaneously to detect and characterize a wide range of weld fabrication defects as they occur for example, a lack of side wall fusion, inclusions and porosity. Transmitted compression waves are effective at detecting all these defects, and distinguishing between them.

2. Measurement Of Tubes At High Temperatures

The measurement of tubes by using the ultrasonic testing has been done by Kazys et. al (1995) to test zirconium tubes used in the channel type of nuclear reactor. The test was conducted during operation since the plant is impossible to shut down. Kazys et al, used ultrasonic test method which was based on the measurement of times-of-flight of ultrasonic waves, reflected from the opposite inner walls of the tube filled with water. This is shown in Figure 6. In this technique, the time-of-flight is compared with a reference channel, where the distance is precisely known. These measurements are performed along a straight line drawn between the opposite walls through the centre of the tube. If the transmitters and receivers of the ultrasonic waves are located along this line, the inner diameter D_{in} can be determined. For this purpose, a probe having at least two measurement channels and a reference channel is used (Figures 7 and 8). The transducers in each measured channel send ultrasonic waves in the opposite directions from the centre of the tube. Each transducer is used both to transmit and receive the ultrasonic pulses. During the test, the tubes were filled with water and the measuring probe was rotated or translated along the tube axis. This scanning was performed by means of an electric motor and precise micrometric screws.

The waveforms of the ultrasonic pulses reflected from the front and back walls of the tube are shown in Figure 9. Multiple reflections between the walls take place and it is possible to observe up to 12 reflected pulses. The waveforms presented indicate that reliable time-of-flight measurements can be performed using the zero-crossing technique.

3. Measurement At High Temperatures In Manufacturing

Measurements of the defects and physical properties of a material using ultrasonic technology are becoming more important nowadays. Different types of ultrasonic applications are studied. Hongerholt et.al. (1997) has studied the ultrasonic sensor based powder injection moulding process, Gronau and Regener (1997) studied the ultrasonic testing of extruded and rolled green compacts from TiAl, Jizhen Xia (1991) studied the ultrasonic testing methods for hot-rolled steel bars of medium and small diameter and Wadley et.al. (1986) studied the internal temperature distribution in the metal continuous caster.

The defects of the powder metallurgy product which is in the injection process can be detected via ultrasonic sensor technology are short shot, weld lines, flash and sticking. A Graphical User Interface (GUI) based ultrasonic data acquisition, data analysis and instrument control system were developed under the Lab Windows environment. The data acquisition system enables the ultrasonic data to be collected throughout the entire moulding cycle. The ultrasonic data are processed instantenously. Processing of the data involves implementing feature extraction and neural network algorithms designed for defect detection and classification. A schematic illustration of the equipment used to measure the defect of the product during the powder injection process done by Hongerholt et.al., is shown in Figure 10. In the experiment, a 30-ton Eigel moulding machine was used. A 100 MHz A/D Gage card was used to digitise the ultrasonic waveforms. In this system, ultrasound was generated using a pulse/receiver unit from Krautkramer

Branson USIP-12 flaw detector. Figure 11 is a schematic illustration showing the geometry and dimensions of one side of the mould insert used during the studies. The specimen produced using this insert is a flat plate. The ultrasonic wave is generated in the mould insert with a 5 MHz centre frequency normal beam longitudinal wave transducer. The wave propagates towards the mould insert/specimen interface, then reflects off this interface and propagates back to the transducer that received the signal. When the mould cavity is emptied, all of the ultrasonic energy that reaches the mould insert/specimen interface reflected back towards the transducer. However, when the mould cavity begins to fill, the amount of energy that is reflected back depends on the material properties and the boundary conditions at the interface. The selected ultrasonic data are used to monitor the powder injection moulding process. A defect free conditions are shown in Figure 12. These data represent the normalised amplitude profile of the ultrasonic wave reflected from the mould insert/specimen interface. If sufficient packing or incomplete fillings occur, the amplitude of the profile will quickly rise back to unity. Rise in amplitude is attributed to weld line defects. In addition, flash results in slightly lower amplitudes across the entire profile (Hongerholt et.al, 1997).

Gronau and Regener (1997) reported the correlation between the microstructure of extruded elemental powder semi-finished products from TiAl and the ultrasonic attenuation and ultrasound velocity. The experiment was performed by, a fast AD-converter which has a sampling rate of 100 MHz per channel or 200 MHz in multiplexing respectively (PAD82a, Spectrum, Siek) with 8 bit resolution and it is equipped with a 64 K sample memory per channel. This measurement system consists of an X-Y scanning stage with transducers attached, an immersion tank, a PC and an ultrasonic pulse/receiver USIP 12. A schematic diagram of the measurement system is presented in Figure 13. The complete control of the measurement system is realised by means of a PC. The program used for controlling, measuring and analysing was written using the National Instruments Lab-VIEW^{TM} software package. The serial interface was used to control the scanning system. To realise a more homogeneous coupling between the transducer and the test specimens, the experiments were carried out in a water bath tank (Gronau & Regenar, 1997). They concluded from the investigation that the titanium agglomerates which led to crack-like discontinuities during the rolling process due to the decreased plasticity of titanium opposite to aluminium were highlighted by increased attenuation values. The ultrasonic velocity measurements make possible the distinction of extruded and rolled material from its chemical composition. The comparison between the peak value method and the cross-correlation for the determination of the ultrasonic time-of-flight shows that the time-of-flight calculated by means of the latter procedure displays a smaller variance. Therefore, for an automated control the cross-correlation appears better qualified, because it delivers also good results for small bandwidth transducers and noisy signals.

Another test reported by Jizhen Xia et.al. (1991), for measuring hot rolled steel bar of 40-60 mm, using the S probe method and the CTS-23 type flaw detector. The probes they used were 2.5P20 (2.5 MHz, PZT, 20 mm diameter), 2.5P14 (2.5 MHz, PZT, 14 mm diameter), 5P14 (5 MHz, PZT, 14 mm diameter) and 5N14 (5 MHz, 14 mm diameter-a narrow pulse probe), and a 5P14 (5 MHz, PZT, 14 mm diameter). The results are shown in Figure 14. The SR probe method uses a CT-1 type flaw detector, which consists of 5P12 × 10 × 2S3 (5 MHz, PZT, piezocrystal of size 12 × 10 mm, two-piece, initial incidence angle 3° when the probe face is plane; with the following probes the same), 5P12 × 10 × 2S6 and 5P12 × 10 × 2S9. The results are shown in Figure 15. The SD probe method used a CTS-26 type flaw detector made by Shan-tou China for matching. The probe was 5P14, with its delay block made of organic glass. On the outside of the delay block is a sound-trap interface which is used to eliminate interference from echoes within the delay block (Xia et. al, 1991).

Wadley et. al. (1986) suggested the importance of positioning ultrasonic sensors at various stages such as in the process for the concentration of dispersion and the continuous chemical composition in the liquid-metal internal-temperature distribution during solidification, and the detection of its discontinuities after solidification, (shown in Figure 16).

Conclusion

The use of the ultrasound is important in high temperature applications. This paper illustrates a few applications of ultrasonic measurements at high temperature which become widely used and has a wide range of applications. That is due to the demand of the industries to measure the quality of their products during production. This helps reduce the number of rejected products in industries. The example of this application is the use of ultrasonic technique to detect the product characteristic on the powder injection moulding process. There were some applications in the power plant which dealt with the high pressures liquids or vapour. The plant is impossible to shut down, therefore the high temperature ultrasonic measurement technique is useful to detect the defect of the tubes and may be used to estimate the life cycle of the tubes. The use of the ultrasound technique at high temperatures is also useful in steel manufacturing to detect the mechanical characteristic of the steel produced when it is still hot. In the welding technology, the crack and the porosity can be measured during the welding process by using this technique. However not all ultrasound probes are designed for this purpose.

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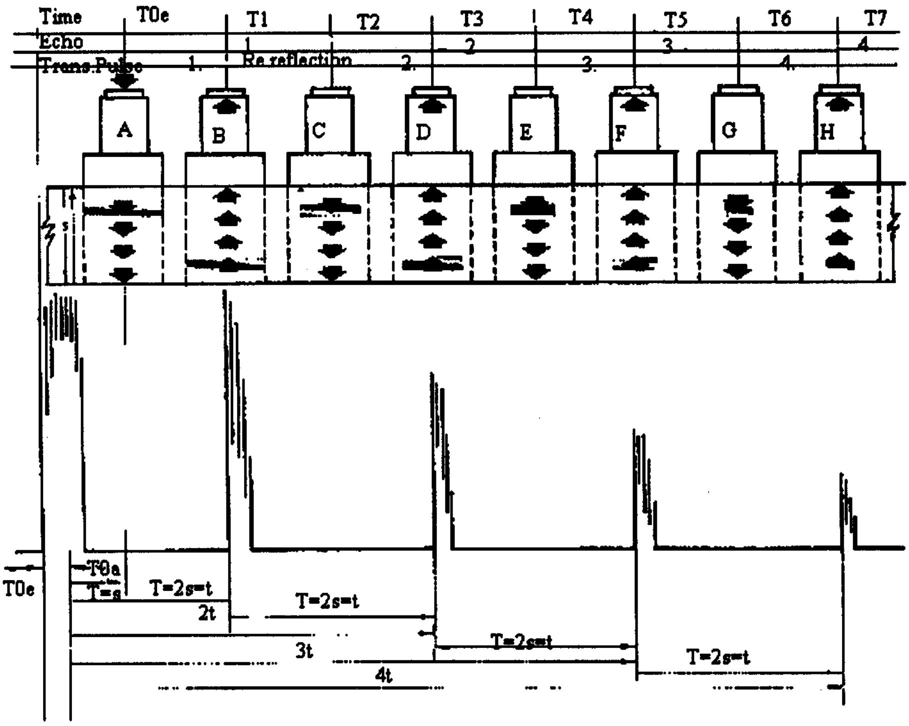


Figure 1 Showing Transducers A to H. Where, T0e = electrical O point; T0a = acoustical O point, and; t = thickness in mm. (Source: AGARDograph No 201 Vol. 1)

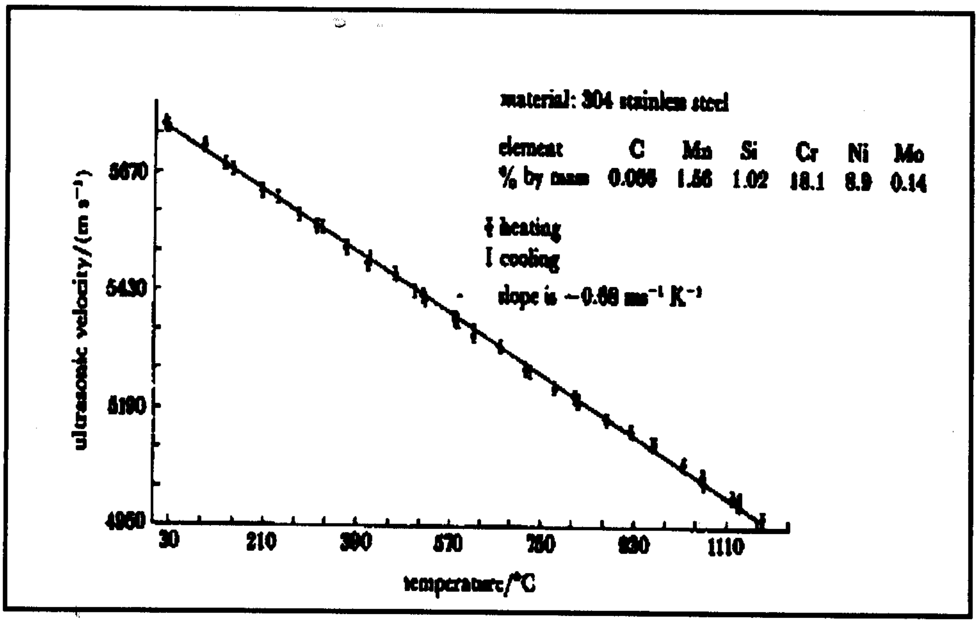


Figure 2. Ultrasonic Velocity Against Temperature For AISI 304 Stainless Steel. (Source: Wadley H.N.G, Norton S.J., Mauer F. and Droney B., "*Ultrasonic Measurement of Internal Temperature Distribution*". Phil. Trans. R. Soc. Lond. A, pp. 352, 1986)

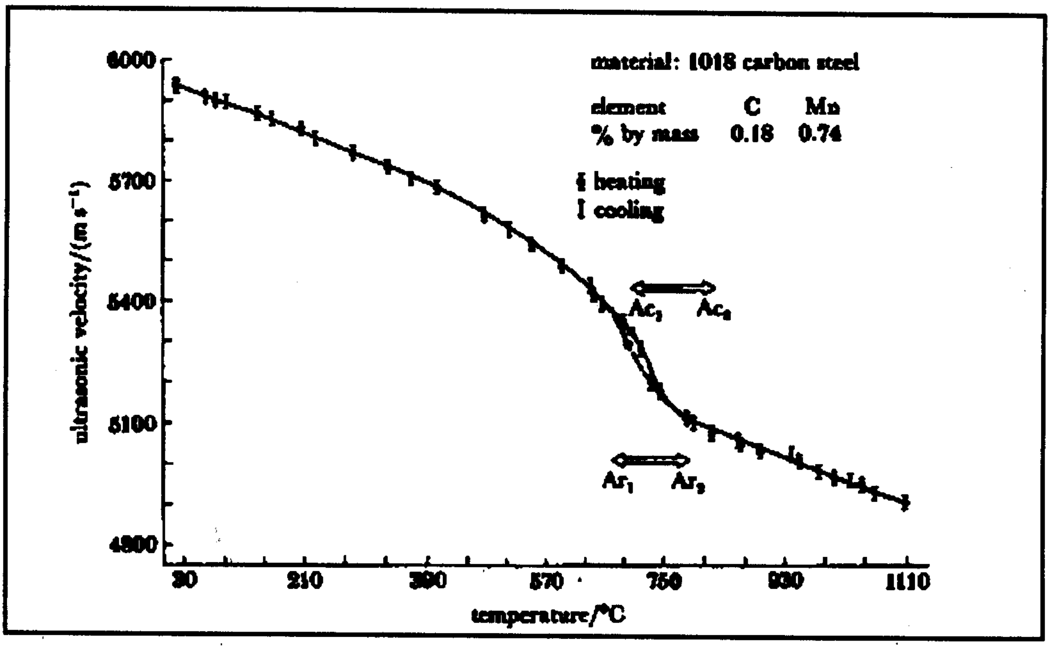


Figure 3. Ultrasonic Velocity Against Temperature For AISI 1018 Carbon Steel. (Source: Wadley H.N.G, Norton S.J., Mauer F. and Droney B., "*Ultrasonic Measurement of Internal Temperature Distribution*". Phil. Trans. R. Soc. Lond. A,pp. 353, 1986)

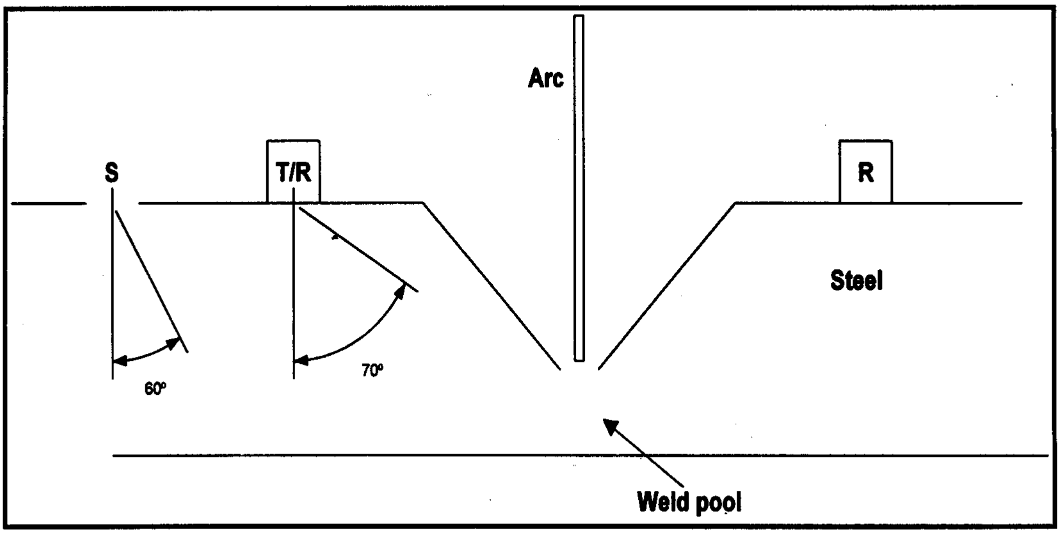


Figure 4. A schematic diagram to show arrangement of Ultrasonic probes used to monitor root-pass welds; S is pulse-echo shear probe. T/R pulse-echo compression probe and R is transmission receiver probe (compression).

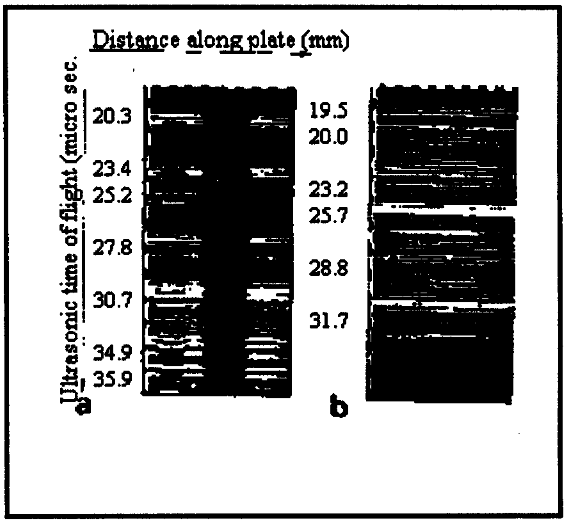


Figure 5. An Ultrasonic B-Scan Data obtained from machined specimen containing simulated defects: (a) Transmitted Compression Waves; (b) Pulse-Echo Compression Waves. (Source: Stares I.J., Duffill C., Ogilvy J.A and Scruby C.B., *"On-Line Weld Pool Monitoring and Defect Detection Using Ultrasonic"*. NDT International Vol.23 No.4, pp 196,1990)

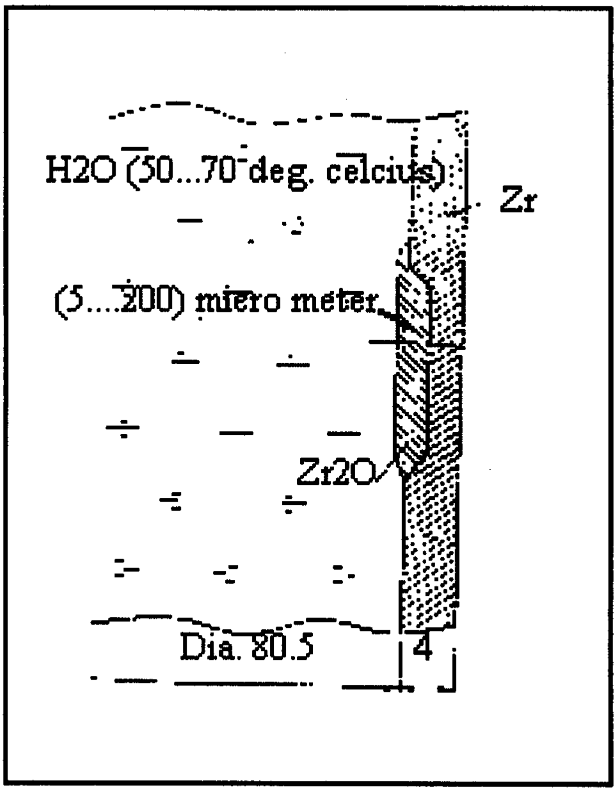


Figure 6. Wall Structure of a Zirconium Tube used in Channel-Type Nuclear Reactors. (Source:Kazys R., Mazeika L., Sliteris R. Vladisauskas A., Voleisis A. and Kundrotas K., *"Ultrasonic Measurement of Zirconium Tubes used in Channel Type Nuclear Reactor"*. NDT&E International Vol.29, No. 1 pp 38, 1995)

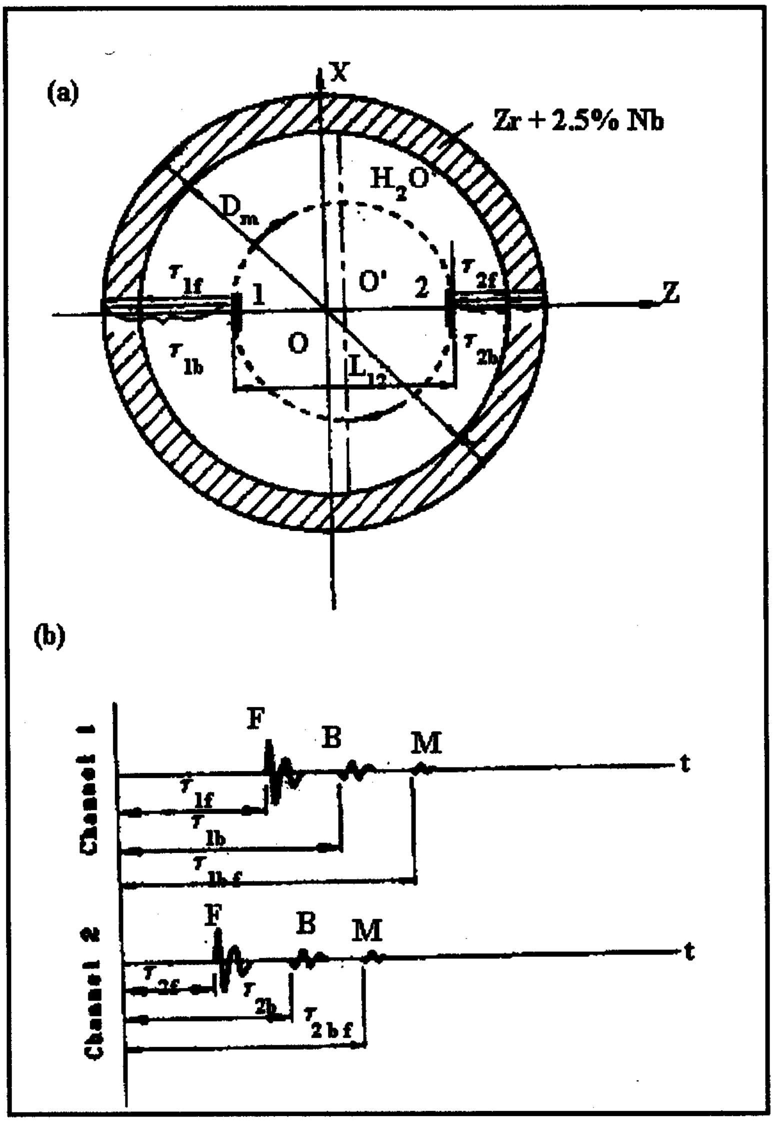


Figure 7. Principle of measurement (a) Location of transducers 1 and 2 inside the tube. The centre of the measuring probe O is shown shifted from the symmetry axis of the tube, coinciding with the origin of coordinates O; (b) Time diagrams illustrating the measurement process; F, B and M correspond to ultrasonic pulses reflected from the front wall, back wall and multiple reflections between walls respectively. (Source:Kazys R., Mazeika L., Sliteris R. Vladisauskas A., Voleisis A. and Kundrotas K., *"Ultrasonic Measurement of Zirconium Tubes used in Channel Type Nuclear Reactor"*. NDT&E International Vol.29, No. 1 pp 38, 1995)

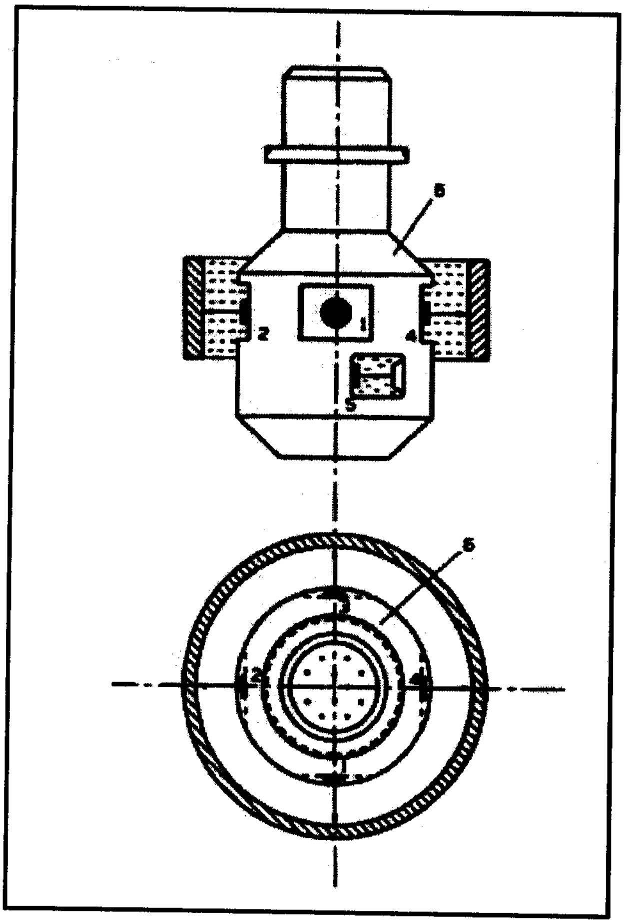


Figure 8. A schematic view of the ultrasonic measuring probe with four measuring channels (Ultrasonic Transducers 1, 2, 3, 4) and reference channel (Ultrasonic Transducer 5); and 6-brass housing. (Source:Kazys R., Mazeika L., Sliteris R. Vladisauskas A., Voleisis A. and Kundrotas K., *"Ultrasonic Measurement of Zirconium Tubes used in Channel Type Nuclear Reactor".* NDT&E International Vol.29, No. 1 pp 39, 1995)

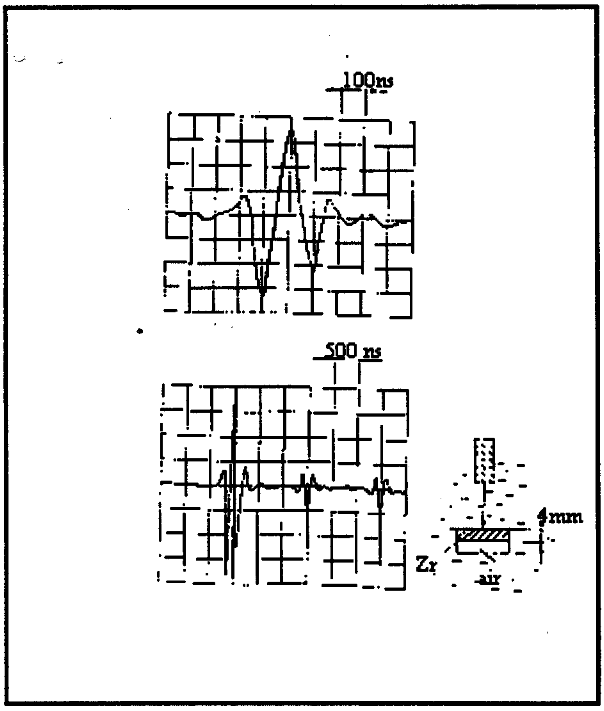


Figure 9. Experimentally obtained waveforms of the ultrasonic pulses, reflected from the walls of the Zirconium tube. (Source:Kazys R., Mazeika L., Sliteris R. Vladisauskas A., Voleisis A. and Kundrotas K., *"Ultrasonic Measurement of Zirconium Tubes used in Channel Type Nuclear Reactor"*. NDT&E International Vol.29, No. 1 pp 44, 1995)

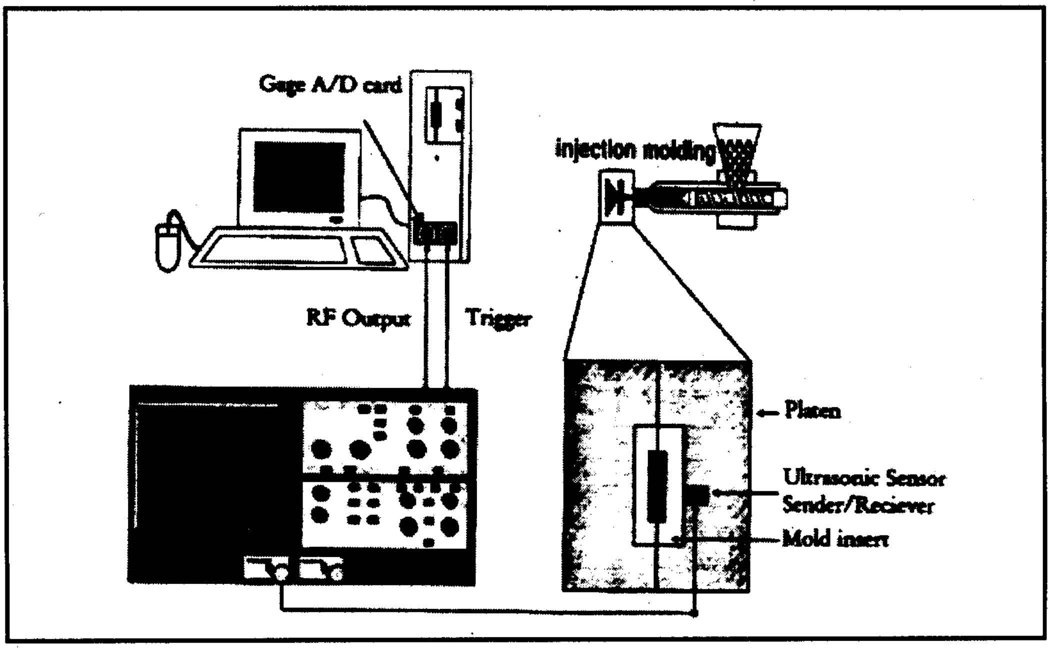


Figure 10. A schematic illustration of the data acquisition system and the experimental set-up. (Source: Hongerholt D.D., Rose J.L., German R.M., *"A Self-Turning Ultrasonic Sensor Based Powder Injection Moulding Process"*. NDT&E International, Vol.30, No.6, pp 393, 1997)

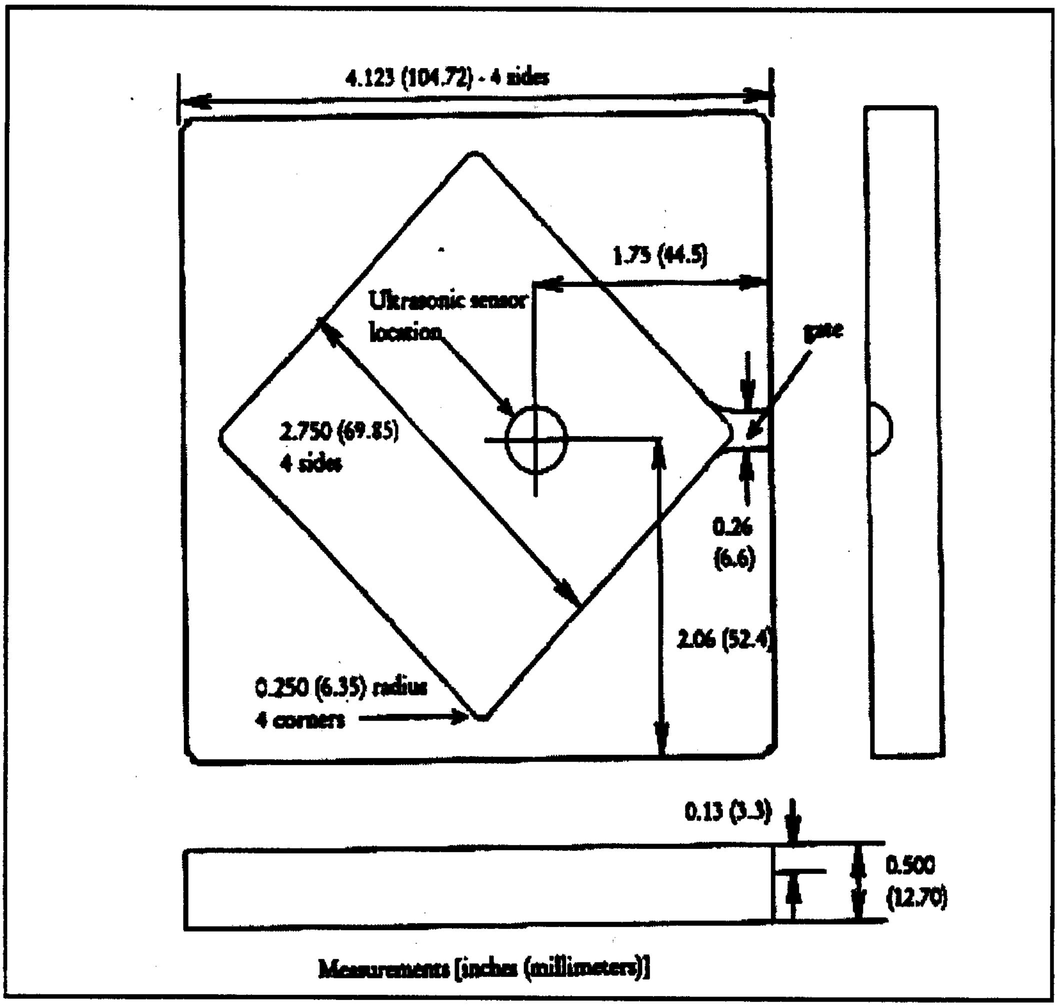


Figure 11. A schematic illustration showing the geometry and dimensions of one side of the Mold Insert used during the studies. The position of the Ultrasonic Sensor is also indicated. The specimen produced with this insert is a flat plate. The mating side of the insert is a flat surface. (Source: Hongerholt D.D., Rose J.L., German R.M., "*A Self-Turning Ultrasonic Sensor Based Powder Injection Moulding Process*". NDT&E International, Vol.30, No.6, pp 394, 1997)

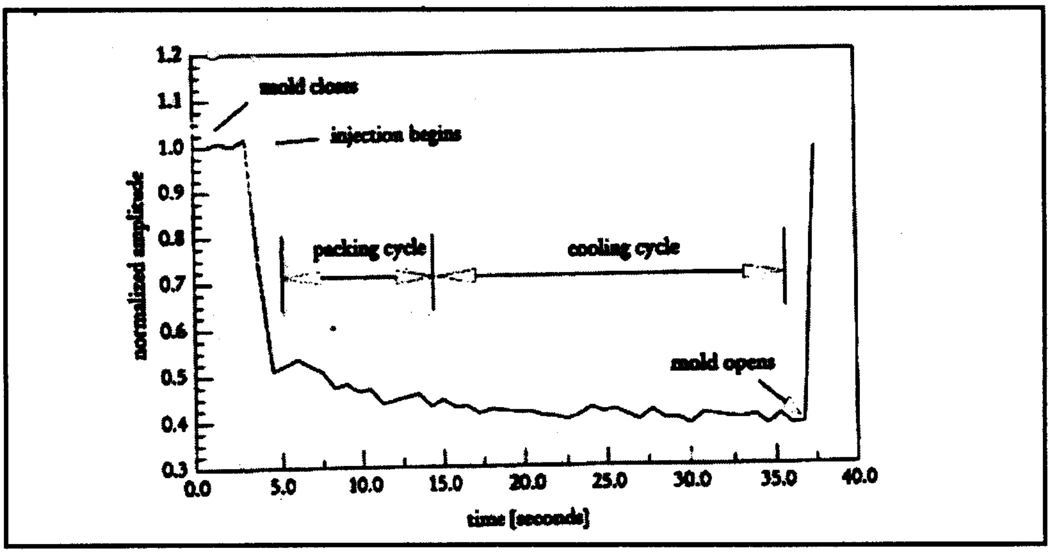
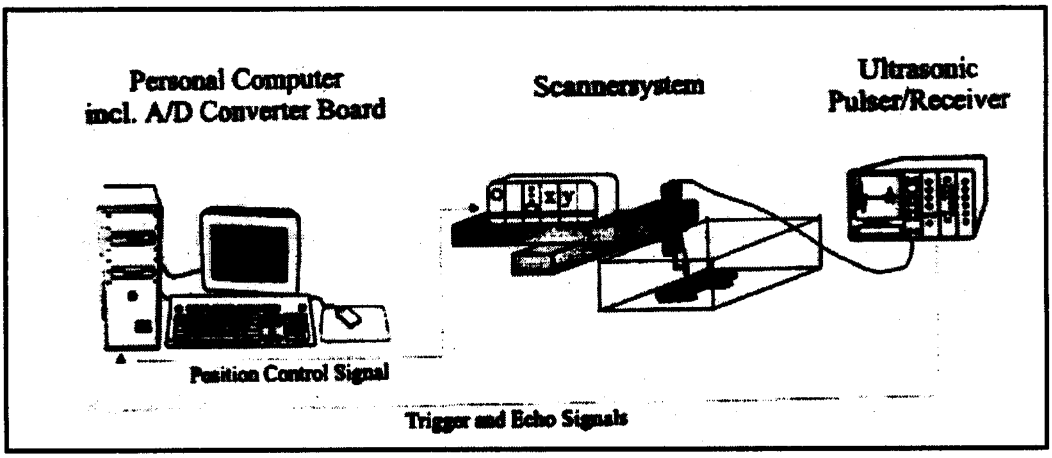


Figure 12. The Ultrasonic Profile collected with The Manufacturing Variables on a defect-free specimen. Several critical points of the manufacturing processes are defined in the Ultrasonic Amplitude Profile. (Source: Hongerholt D.D., Rose J.L., German R.M., "*A Self-Turning Ultrasonic Sensor Based Powder Injection Moulding Process*". NDT&E International, Vol.30, No.6, pp 393, 1997)



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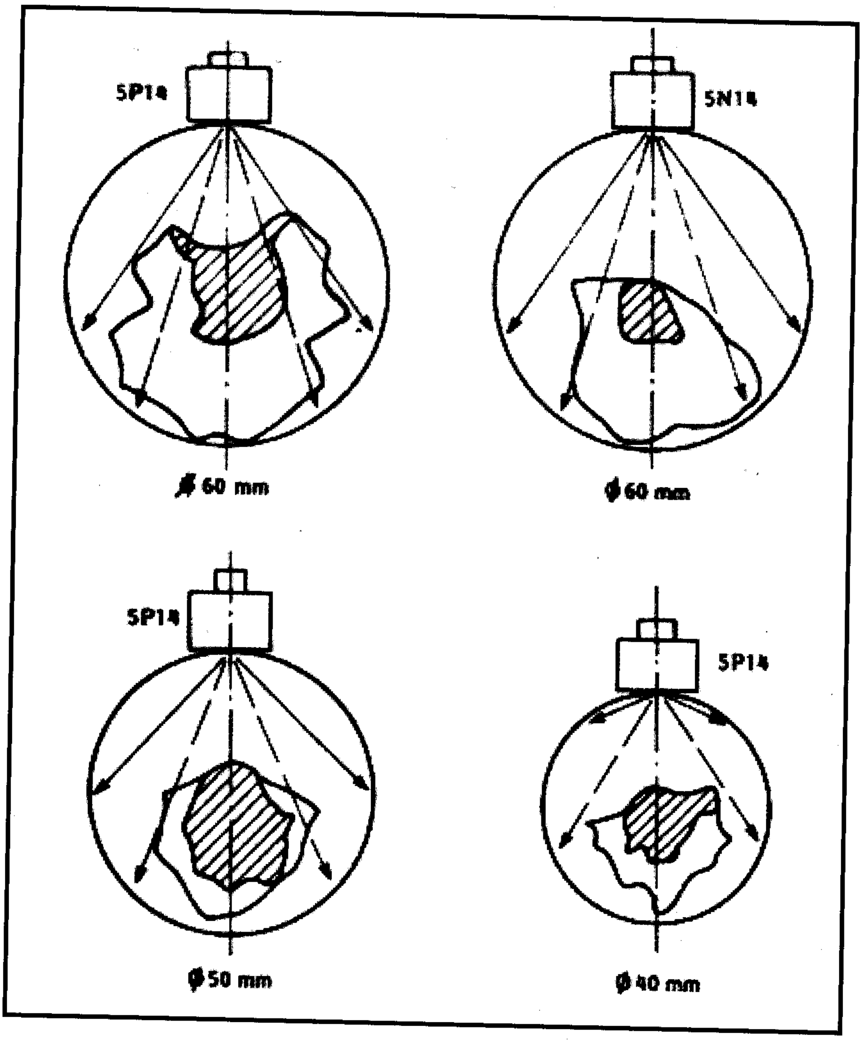

Figure 14. Results with the S Probe. (Source: Xia J., Sun H., Fong X. and Huang F., "*Reliability of Ultrasonic Testing Methods for Hot-Rolled Steel Bars of Medium and Small Diameter*".NDT&E International, Vol. 24, No.6 pp 314, 1991)

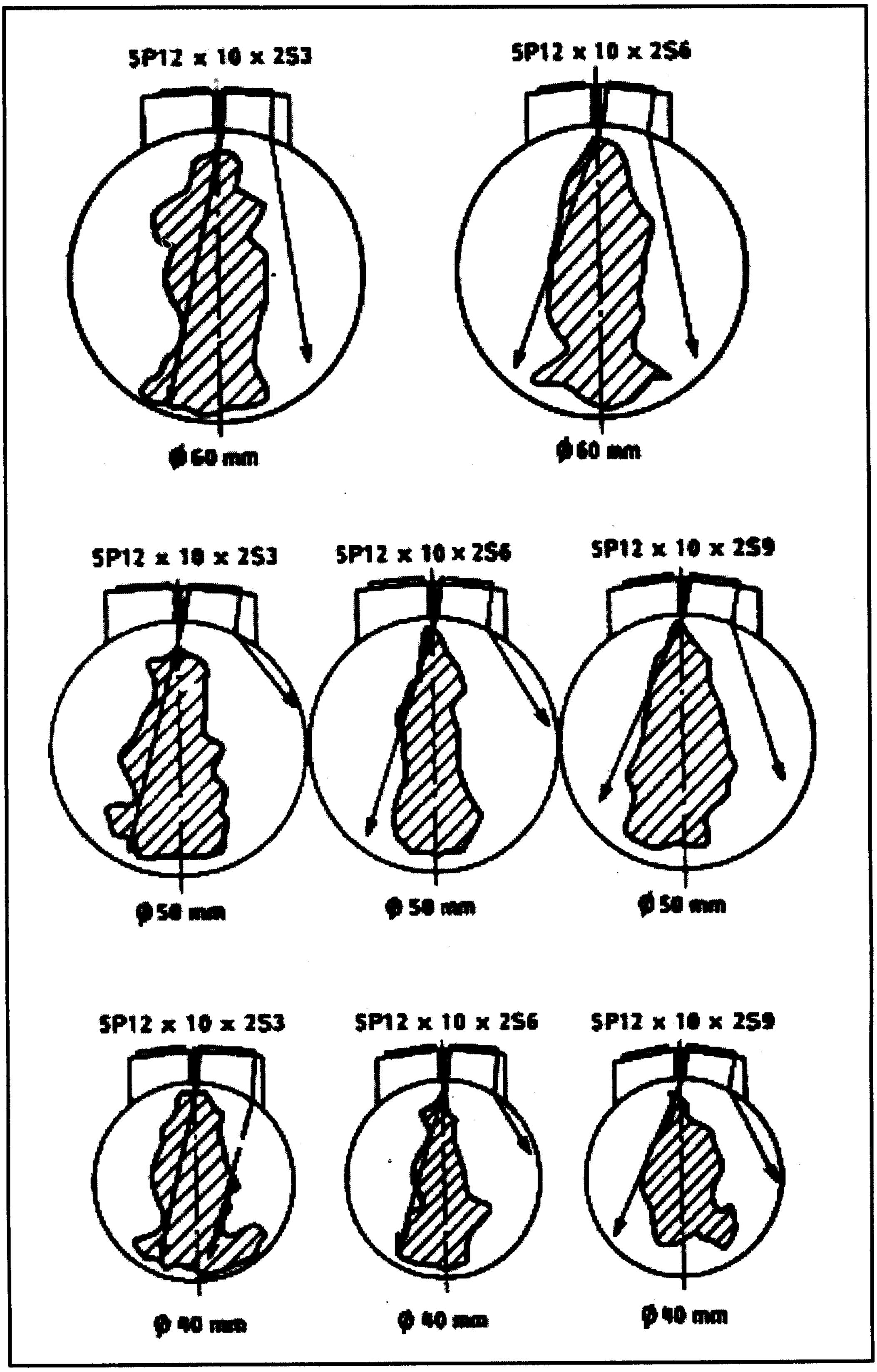

Figure 15. Results with the SR Probe. (Source: Xia J., Sun H., Fong X. and Huang F., "*Reliability of Ultrasonic Testing Methods for Hot-Rolled Steel Bars of Medium and Small Diameter*". NDT&E International, Vol. 24, No.6 pp 314, 1991)

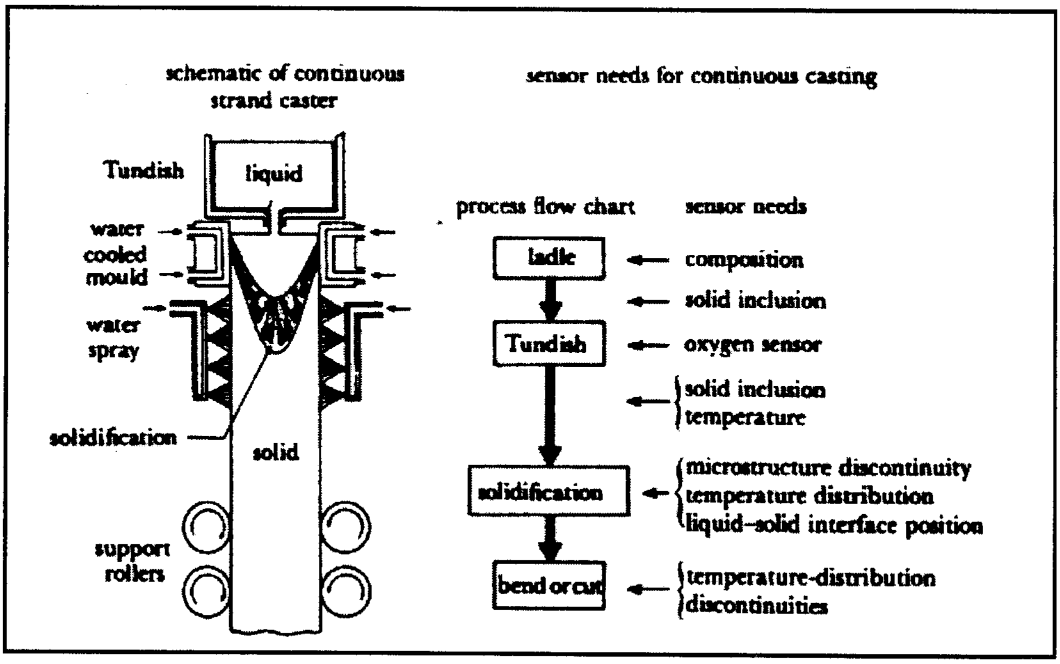

Figure 16. A schematic diagram of a Metal Continuous Caster and the sensor needs for the casting of steel. (Source: Wadley H.N.G, Norton S.J., Mauer F. and Droney B., "*Ultrasonic Measurement of Internal Temperature Distribution*". Phil. Trans. R. Soc. Lond. A,pp. 342, 1986)