

**DEVELOPMENT OF A LASER SCANNING SYSTEM
FOR THE INSPECTION OF SURFACE DEFECTS**

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DECLARATION

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Master of Science in Mechanical Engineering is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work

Signed Shane Beary Date 6 FEB '97
Candidate

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ABSTRACT

DEVELOPMENT OF A LASER SCANNING SYSTEM FOR THE INSPECTION OF SURFACE DEFECTS

**BY
SHANE BEARY**

The main objective of this project is the development of a low cost laser scanning system for the detection of surface defects. The inspection system is based on a laser sensor, power supply unit and an X-Y table. All of these components are interfaced with a personal computer. The system developed is capable of measuring surface defects within the range of greater than or equal to 1mm. For the experiments carried out it was intended to assess the sensors measuring ability under certain headings. The two main headings covered were accuracy and repeatability. Other important subjects included examining the measuring limits of the system, examining the effect of using materials of different reflection abilities, and the possible cause of errors in the system.

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CHAPTER ONE

CHAPTER ONE

1 - Introduction

On-line control plays an increasingly important role in modern manufacturing processes. The introduction of laser scanning control systems into the manufacturing process allows 100% material testing and prevents defects and production deterioration from being undetected. The principals of optical inspection used by these systems are of a non-contact nature. Thus they can be applied at all the usual temperatures, allow a high resolution (e.g. pinholes down to $10\mu\text{m}$ in size can be detected), and can be easily adapted to the requirements of automated inspection of continuously moving parts. Illumination with monochromatic laser light provides images of better quality and allows frequency filtering which is very important when working under normal illumination. Scanning infers that one point at a time is illuminated from one single direction. Thus in practice, an image with high contrast and resolution can be captured.

Laser scanning systems have been successfully implemented in the inspection of widely varied material surfaces. In the plastic industry for example, standardised inspection systems now exist for transparent, coated or coloured films (photographic films, video tapes, audio tapes, filters, protective films etc.) and plates. The most commonly occurring types of faults in these materials are inclusions, holes, bubbles, inhomogenities, surface defects (scratches, indentation, pitting) and defects in coatings. It is usually required not only to detect faults but also to classify them. To enable types of faults to be distinguished unambiguously, a catalogue of these is first assembled for each material. From this the optical characteristics of the individual types of defects are determined and summarised as a defect matrix i.e. type of defect/inclusion, scratches or indentation against the mode of observation. Inspection of the material immediately following its production helps to prevent situations where unusable material is produced over a long period. This thesis is mainly concerned with how the type of surface defects encountered in the

manufacturing industry can be measured. It outlines the experimental results of the laser scanning system developed when using different sample materials, mainly metals and plastics.

The main objective of this project is the development of a low cost laser scanning system for the detection of surface defects. The inspection system is based on a laser sensor, power supply unit and an X-Y table. All of these components are interfaced with a personal computer. The system developed is capable of measuring surface defects within the range of greater than or equal to 1mm.

In this thesis the literature survey is presented in Chapter 2, which is mainly concerned with lasers, scanning technology and laser scanning inspection systems. The configuration of the inspection system is described in Chapter 3, which includes the laser sensor, X-Y table, the computer interfaces and the software used to control the measurement process. The principle of optical triangulation which is used as a non contact method of determining defect measurement is also presented and discussed. A description of the software developed for the measurement process is presented along with how the software was used in a sample measurement process.

Chapter 4 outlines the experimental results which were carried out using the developed system. For these experiments six different workpiece materials were used. These included Aluminium, Stainless Steel, Brass, Copper, Polycarbonate and Perspex. Different materials were used in order to compare the system performance on materials of different reflective capabilities. Also in all the six workpiece materials defects in the form of holes varying from 8mm to 1mm were incorporated into detection. The different size holes were used to test the measuring limits of the laser sensor. The performance of the system with regard defect size and material reflective properties is summarised at the end of this chapter. The conclusions and recommendations for further work are outlined in Chapter 5. These include a look at both the systems hardware and software development as well as analysis of the experimental results.

CHAPTER TWO

CHAPTER TWO

2.- Literature survey

2.1 - Lasers

A laser is a device which produces and amplifies light [1]. The acronym LASER stands for light Amplification by Stimulated Emission of Radiation. The word light refers to ultraviolet, visible or infrared electromagnetic radiation. The word radiation refers to electromagnetic radiation of which light is a special case. The key words in the acronym are amplification by stimulated emission. A laser amplifies light and it does this by means of the phenomenon of stimulated emission. Most, but not all, lasers are also oscillators because an optical resonator is used to provide feedback and energy storage. Laser light has many advantages over an ordinary light source. There are several key properties of laser light which ensure that lasers are such useful tools in an incredible variety of applications. The primary properties of concern in industrial applications are radiance, directionality, monochromaticity, coherence and the various forms of output.

2.2 - Properties of lasers

2.2.1- Radiance

The radiance of a source of light is the power emitted per unit area of the source per unit angle [2]. The units are watts per square metre per steradian. A steradian is the unit of solid angle which is the three dimensional analogue of a conventional two-dimensional (planar) angle expressed in radians.

The term brightness is a term frequently used instead of the proper term luminance. Luminance is like radiance except that the response of the standard eye is taken into account, and therefore only applies to visible light. The units are lumens per unit area.

per unit solid angle. A lumen is the photometric equivalent of a radiometric unit (absolute unit of power), the watt. The field of photometry takes into account the eye response whereas the radiometry deals with absolute physical quantities. However, the usual practice is normally to only deal in radiometric quantities.

Lasers generally have an extremely high radiance output. For example, a helium-neon laser with an output of 1mW will have an output spot diameter of about 1mm and a beam divergence of about 1mrad. The radiance of the sun in contrast is only $1.3 \times 10^6 \text{ W/m}^2/\text{sterad}$ even though the sun emits a power of $4 \times 10^{26} \text{ W}$.

Radiance is an extremely important concept. High radiance obviously means that a beam has a small divergence angle unless the power is very large. Lasers achieve high radiance at relatively low power levels. The amount of power that can be concentrated on a spot by focusing a beam of light is directly proportional to the radiance. In laser work an important concept is the irradiance (also called intensity). Irradiance is the power per unit area falling on a surface at a given point. For convenience the units are usually given as watts per square centimetre (W/cm^2). For example a HeNe laser beam could be focused by a 2.5cm focal length lens to an irradiance of over 200 W/cm^2 . The spot diameter of the beam would only be about $25 \mu\text{m}$. High irradiances are important to such materials processing applications as cutting, drilling and welding. However, the spot size required is of the order of 0.1-1.0mm for most applications. One thousand watts focused to a 0.1mm diameter spot produces an average irradiance of nearly 13 MW/cm^2 . This is still very high compared with what can be achieved with conventional methods.

The high radiance of lasers' results in small spot sizes when mirrors or lens are used to focus the beam. This is what then produces the very high irradiance. Therefore the radiance of a laser is directly linked to the small beam divergence (directionality) of a laser.

2 2 2 - Directionality

Everyone has seen the publicity spotlights at circuses and big events. Their beams of light penetrate the heavens, apparently diverging little as they disappear into the night sky. While these spotlights produce beams that don't expand much over hundreds of yards, a laser beam the same size would propagate hundreds of miles without expanding much.

The divergence of lasers are typically measured in milliradians. This very small divergence results from the requirement that light must make many round trips of the laser resonator before it emerges through the partially transmitting mirror. Only rays that are closely aligned with the resonator's centreline can make the required number of round trips, and these aligned rays diverge only slightly when they emerge [3]. But just as it's impossible for a laser to be perfectly monochromatic, it is impossible for a laser to produce a nondiverging beam of light. Although the divergence of a laser beam can be very small when compared to light from other sources, there will always be some divergence.

In effect, the beam of light from a laser is a narrow cone of light that appears to be coming from a point. As such, geometry plays no role in the focusing of a laser beam, at least not the raw beam or one that has simply been expanded or reduced in size. The limiting effect which is a basic property of light is diffraction. Diffraction causes collimated beams of light to diverge and causes bending of light beams around sharp edges of objects. It also limits the size of a focused spot. A lens with an f -number (the ratio of the lens focal length to aperture or beam size) of one will focus an ideal diffraction limited laser to a spot radius approximately equal to the wavelength of the light. Clearly, a 1mm focal length lens would be impractical, but if the beam is expanded to 1cm in diameter, then a 1cm focal length lens would be practical and achieve the desired result. Places where such small spot sizes might be required are integrated circuit manufacturing and recording and reading of optical data storage media such as laser video or audio discs and optical memories for computers.

2.2.3 - Monochromaticity

The term monochromatic literally means single colour or single wavelength. In order to understand this concept observe the following process [4]. Because a glass prism is dispersive, it separates white light into its component colours. The bandwidth of white light is as wide as the whole visible spectrum, about 300 nanometers (nm). If light that is nominally red falls on the prism, it is separated into its nominal wavelengths too. But, in this case the bandwidth is far less, perhaps only 10 or 20nm. The prism will produce a narrower band of colours, ranging from dark red to light red. However the prism will not have any discernible effects on the red laser light because its bandwidth is very small when compared with the red light from the filter. For example the bandwidth of a HeNe laser is typically less than 1nm.

However, no light source can be perfectly monochromatic. Lasers tend to be relatively monochromatic but this depends on the type of laser in question. Monochromatic output, or high frequency stability, is of great importance for lasers being used on interferometric measurements since the wavelength is a measure of length or distance and must be known with extreme precision and it must remain constant with time. The same holds true for lasers used in chemical and many other scientific analytical applications. Precise wavelength definition is not generally considered important in materials processing though some infrared wavelengths are thought to work better in cutting or drilling of certain polymers, but generally in processes controlled by thermal effects precise wavelength control is not critical. However, processing of polymeric materials with ultraviolet wavelengths, such as are available from excimer lasers, is entirely different. In this case precise tuning of the wavelength to resonate with the molecular bond will probably significantly enhance the efficiency of material removal. Absolute monochromaticity is an unattainable goal which we can only approach by refining our light sources.

2 2 4 - Coherence

The easiest way to explain the concept of coherence is the marching band analogy [5] In a parade of marching bands one would see a nearly perfect spatial coherence across the rows and columns. If we know the position of one marcher, it is probable to know the relative position of any of the other marchers in the band. An incoherent light source on the other hand is more analogous to the people on a busy city road at rush hour. The concept of coherence is one of considerable interest in a wide variety of laser applications such as communications, holography, doppler velocimetry and interferometric measurements. Lasers provide a high radiance source of light with a high degree of coherence. This combination is not available from any other source of light.

A coherent light beam will have three distinct characteristics

- 1 the same wavelength
- 2 the same direction
- 3 the same phase

The wavelength is the distance between two like points on a wave. The light waves in a laser beam all have the same wavelength. The phase of a wave, in its most practical sense, refers to its position relative to another wave. If two waves are in phase, they are lined up in space and time. If the waves are shifted in respect to one another, then they are out of phase by a given amount. What's more, the light from a laser exhibits both spatial coherence and temporal coherence. Its spatial coherence means that light at the top of the beam is coherent with the light at the bottom of the beam. The farther you can move across the beam and still find coherent light, the greater the spatial coherence. Temporal coherence, on the other hand, comes about because two waves in a laser beam remain coherent for a long time as they move past a given point. That is, they stay in phase with each other for many wavelengths. Coherence also causes a problem called laser speckle. Speckle is produced when laser light is

scattered from a diffusing surface Speckle can be used in some measurement applications, but can create problems in others

All the things that can only be done using laser light can be done because laser light is coherent Monochromatic laser light can be used to probe the structure of atoms or to control complex chemical reactions - because it is coherent Highly directional laser light can transport energy over large distances or focus that energy to very large intensities - because it is coherent Phase consistent laser light can produce realistic three-dimensional holograms or create ultra short pulses of light whose duration is only a dozen or so optical cycles - because it is coherent The coherent light from a laser is indeed a different breed of light from that emitted from any other source

2 2 5 - Power and Energy Output

The output of lasers may be pulsed or continuous Lasers used for alignment, measurements and other low-power applications usually have a continuous output whereas materials processing lasers may be either pulsed or continuous Some lasers are capable of both pulsed and continuous operation

2 3 - General Classification of Lasers

There are many different types of laser available for industrial use at the moment The application of each type is dependent on its particular characteristics A brief description of the main lasers in use today and their unique properties [6],[7],[8] is given below

2 3 1 -Helium-neon lasers (HeNe)

- Electrically pumped gas laser
- Bright red beam at 632.8nm and also infrared lines at 1.15 and 3.39 μ m
- Electrical efficiency typically - 0.1%

- Energy is transferred from electrons to the HeNe atoms leaving them in an excited state
- Output power varies from a fraction of a mW up to 50mW
- Operating life - 15,000 to 20,000 hours
- Most common failure mechanism is cathode decay
- Commonly used in supermarket checkout stands, home videodisk players and laser printers

2 3 2 - Molecular lasers

- Operate on the rotational, vibrational and electronic energy levels of molecules
- Most important of these is CO₂ laser which is based on vibration technique
- Capable of generating very high average powers with relatively high electrical efficiency
- Commercial CO₂ lasers with average power greater than 20kW are available, and kilowatt CO₂ lasers are common
- Their electrical efficiency can exceed 10%
- Commonly used for applications such as cutting, welding, and heat treating materials
- CO₂ lasers are also important in medical and research applications
- A newer type of molecular laser, the excimer laser, is important because it is a good source of ultraviolet light

2 3 3 - Solid-state lasers

- Lasing atoms are embedded in a solid piece of transparent material called the host
- Most common examples are Nd YAG lasers, Nd glass lasers, and Cr ruby
- Optical pumping provides the energy to create a population inversion
- Usually water cooled
- Largest application of solid-state lasers is in tactical military equipment, where they are used in rangefinders and target designators

- Also used in materials processing, medicine and scientific research

2 3 4 - Semiconductor diode lasers

- A laser diode is a junction between p-doped and n-doped materials
- The resonator is often formed by polishing the end faces of the semiconductor
- Stimulated emission occurs before an atom has time to lose its energy another way
- Most common type is the GaAs laser
- Wavelength range from 0.33 μm UV - 40 μm IR
- Outputs in the milliwatt range
- Diode lasers are the most ubiquitous lasers in existence
- They are small, rugged and cheap but not powerful yet
- They will probably replace gaseous and optically pumped lasers in a number of applications in the near future

2 4 - Applications of Lasers

Like the laser itself, the applications of lasers involve a wide range of fields. The unique characteristics of laser light are what make lasers so special. The capability to produce a narrow beam doesn't sound very exciting, but it is the critical factor in most laser applications. Because a laser beam is so narrow, it can read the minute, encoded information on a stereo CD - or on the bar-code patterns in a grocery store. Because a laser beam is so narrow, the comparatively modest power of a 200 watt carbon-dioxide laser can be focused to an intensity that can cut or weld metal. Because a laser beam is so narrow, it can create tiny precise patterns in a laser printer. Generally speaking the applications of lasers can be broken down into two separate categories: Low-power applications and High-power applications.

2 4 1 - Low-power Applications

When we talk about low power lasers we generally mean in the 1-50mW range, usually HeNe or diode lasers. The main applications of such a laser are alignment, gauging, inspection, interferometry and holography [9]. The characteristics of lasers which make them useful in these type of applications are high monochromaticity, coherence and high radiance.

Interferometric applications such as holography, speckle, measurements and Doppler velocimetry require good spatial and temporal coherence, as well as varying levels of frequency stability and good mode quality. Laser interferometry is used to make measurements or to control machines and motion systems to within a fraction of a millimetre. The small beam divergence of lasers gives them the unique capabilities in alignment applications whether for machine set up or building construction. The high radiance permits the use of lasers for accurate triangulation measurements and control of machines such as robots.

Laser printers are capable of producing high quality output at very high speeds. Until several years ago they were also very expensive, but since printers based on inexpensive diode lasers were introduced, the cost dropped dramatically. In a laser printer, the laser writes on an electrostatic surface which in turn transfers ink to the paper. Low-power lasers have other applications in graphics as well. Laser typesetters write directly on light-sensitive paper, producing camera ready copy for the publishing industry. Laser colour separators analyse a colour photograph and create the information a printer needs to print the photograph with four colours of ink. Laser platemakers produce the printing plates so that newspapers can be printed in locations far from their editorial offices. Also, laser bar-code scanners are used for the checkouts in a supermarket. The narrow beam of the HeNe laser in these machines scans the bar-code pattern, automatically reading it into the store's computer.

There seems to be no end to the ingenious ways a narrow beam of light can be put to use. In sawmills, lasers are used to align logs relative to the saw. The laser projects a visible stripe onto the log to show where the saw will cut it as the sawman moves the log into the correct position. On construction projects the narrow beam from a HeNe laser guides heavy earth-moving equipment. Laser light shows herald the introduction of new car models and rock concerts. Diode lasers are the light sources in many fibreoptic communication systems. Laser gyroscopes guide the newest generation of commercial aircraft's. Finally, low-power lasers are widely used in industry for automatic on-line inspection processes, and this is the main area which this project is concerned with. These type of applications would not be feasible using conventional light sources.

2.4.2 - High-power Applications

The main application of high-power lasers is in materials processing, where lasers are used to cut, drill, weld, heat-treat, and otherwise alter both metals and non-metals [10]. Lasers can drill tiny holes in turbine blades more quickly and less expensively than mechanical drills. Lasers have several advantages over conventional techniques of cutting materials. For one thing, unlike saw blades or knife blades, lasers never get dull. For another, lasers make cuts with better edge quality than most mechanical cutters. The edges of metal parts cut by laser rarely need to be polished or filed because the laser makes such a clean cut to start with. The major drawback to laser cutting is thickness of the material to be cut. Nd-YAG lasers can cut up to about 5mm thickness and CO₂ lasers can cut up to about 20mm at reasonable speeds. Large amounts of assist gas are required. If oxygen is used, the operating cost can be quite high. However, if air can be used, this cost is virtually eliminated.

Most of the statements concerning cutting apply to hole piercing with solid state lasers. Added to the list should be the fact that holes can be drilled at large angles to the surface. Hole depth-to-diameter ratios of 20:1 are common. High repeatability and accurate placement are achievable. The major drawback to laser hole piercing is

that the holes are tapered and some recast material is usually present in the entrance side, and dross due to oxidation may stick to the exit hole.

Laser welding can often be more precise and less expensive than conventional welding techniques. Moreover, laser welding is more compatible with robotics, and several large machine-tool builders offer fully automated laser-welding systems to manufacturers. There are limitations to laser welding, as with any process. Spot welding with pulsed solid state lasers is limited to about 1-2mm penetration, and continuous seam welding with multikilowatt CO₂ lasers is limited to around 1cm penetration. High carbon steels and certain other alloys are difficult to weld without cracking because of the rapid heating and cooling involved. Reasonably good fitup between parts is required for successful laser welding.

Laser heat-treating involves heating a metal part with laser light, increasing its temperature to the point where its crystal structure changes. It is often possible to harden the surface in this manner, making it more resistant to wear. Heat-treating techniques require some of the most powerful industrial lasers there are, and it is one application where the raw power of the laser is more important than the narrow beam. Although heat-treating is not a wide application of lasers now, it is one which is likely to expand significantly in the coming years.

Lasers started out in research laboratories, and many of the most sophisticated ones are still there. Chemists, biologists, spectroscopists, and other scientists count lasers among the most powerful investigation tools of modern science. Again, the lasers narrow beam is valuable, but in the laboratory the other characteristics of laser light are often important too. Because a laser beam contains light of such pure colour, it can probe the dynamics of a chemical reaction while it happens or it can even stimulate a reaction to happen.

In medicine, the lasers narrow beam has proven a powerful tool for therapy. In particular, the carbon dioxide laser has been widely adopted by surgeons as a bloodless scalpel because the beam cauterises an incision even as it is made. Indeed,

some surgeries which cause profuse bleeding had been impossible to perform before the laser. The laser is especially useful on ophthalmic surgery because the beam can pass through the pupil of the eye and weld, cut or cauterise tissue inside the eye. Before lasers, any procedure inside the eye necessitated cutting the eyeball open.

In summary Table 1 below gives an idea of the main areas of concern for low and high-power applications. Having given a brief insight into these areas I intend now to concentrate on the applications of low-power lasers, specifically the use of lasers as an inspection tool which is the main area of concern of this project.

Low-Power laser applications	High-Power laser applications
Alignment	Surface Hardening
Gauging	Welding
Inspection	Cutting
Interferometry	Laser Marking
Holography	Hole Piercing
	Alloying and Cladding

Table 1 Main applications of lasers

2.5 - Scanning Technology

Besides the laser itself, most laser applications require other components and devices. These components can be divided into the broad categories of modulators and scanners, detectors, positioning systems and imaging optics. This section deals with scanning devices which operate on the laser beam to change its direction. Scanners are used outside the cavity to direct the beam toward a specific location. There are at present three main types of beam deflection. They are mechanical, acousto-optic and electro-optic.

Another method of differentiating between major scanning techniques is shown in Fig 1. This method divides scanning technology into two classes: high inertia and low inertia. This identifies the operational distinction between massive and agile control capability [11].

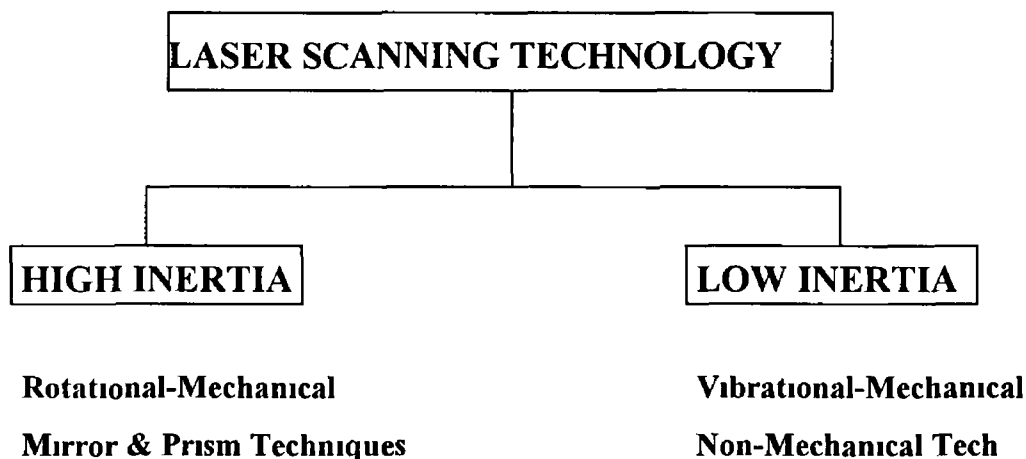


Fig 1 Generalisation of laser scanning technology [11]

2.5.1 - Mechanical scanners

Most laser scanners today use mechanical rotation [12]. The inertia of high speed rotation gives a very stable scan rate, and fine tuning by electronics can increase stability to about one part in 30,000. Depending on the ratio of the facet width to the beam size at the facet, the active writing time can be 95% of the total operating time. Mechanical scanners employ the actual physical movement of a mirror, prism or similar components to alter the direction of the laser beam [13]. The component is generally moved using an electric motor or through a galvanometer/coil arrangement. The prime constraint upon this technology is that it requires a relatively rigid scan format, limited by the intrinsic high inertia of the mechanical system. Other constraints upon rotational-mechanical scanners are the systems parameters which may inhibit the use of rotating components and their associated bearings, motor drive and control systems. Generally mechanical scanners tend to be slow and

difficult to control precisely, but they offer the advantage of relatively low price, durability and simplicity

Galvanometer mirror

The galvanometer mirror works on the same principle as the d'Arsonval movement in an analog meter [14]. A coil of wire mounted between the poles of a permanent magnet will rotate if a current is passed through it. Since the current causes a magnetic field around the coil, the magnetic field of the permanent magnet will repel the coil and cause it to move. Varying the amount and direction of current in the coil will cause it to move different amounts in different directions. A mirror mounted on the coil will move with it and can be used to reflect a laser beam in different directions.

Galvanometer mirrors offer the advantage of a large angle of deflection and little or no distortion of the laser beam. They are available in several different speeds and resolutions. However, they are limited by different parameters [15]. A large scan angle and/or a reasonable beam diameter causes slow scan rates (some few hundreds Hz). A high scan rate (up to 20kHz) causes small mirror sizes and only sinusoidal motion functions. An advantage is that the centre of deflection coincides with the mirror axis. This fact simplifies the optical corrections. Fig 2 shows a common galvanometer mirror. A combination of two such mirrors at right angles to each other can be used to position and scan the laser beam in two directions.

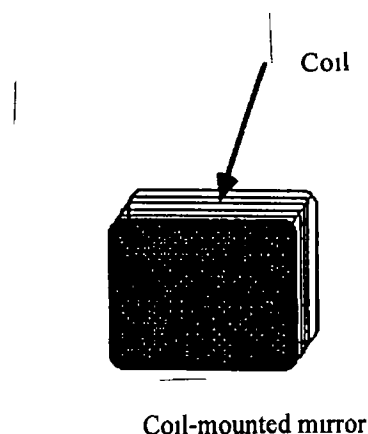


Fig 2 Galvanometer mirror [14]

Rotating mirror

One of the earliest and most familiar rotating mirror techniques is illustrated in Fig 3 [16]. A multifaceted polygon is illuminated with a single narrow beam such that only a fraction of the mirror subtense is exposed to the beam at any time. An angular displacement of the polygon through the angle θ imparts a 2θ angular displacement to the reflected beam. This double speed scan continues until the corner of the polygon encounters the illuminating beam, whereupon the reflected beam is split in two: one part finishing the scan and the balance initiating the new scan. However, this system is optically and mechanically inefficient since only a small fraction of the mirrored surface is actively engaged in reflecting the illuminating beam.

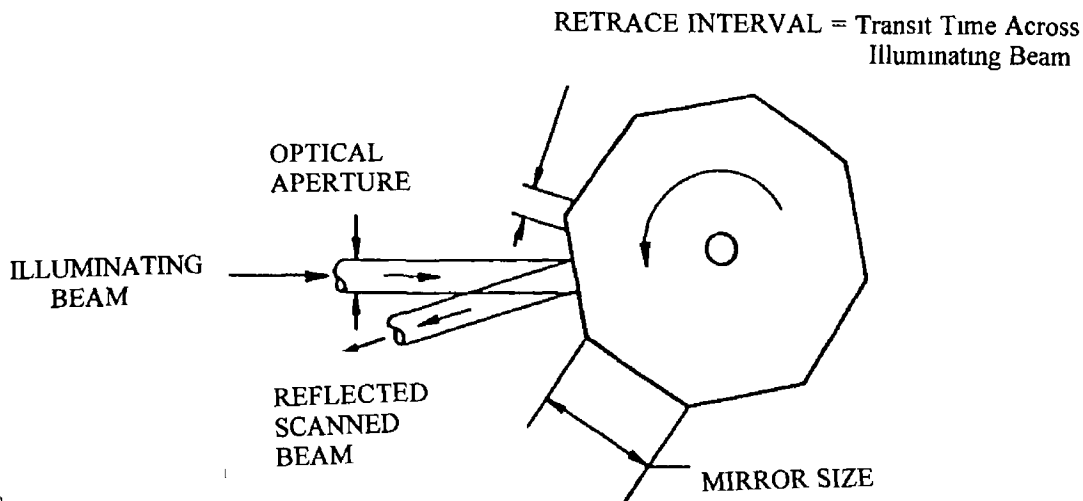


Fig 3 Partially illuminated polygon [16]

Rotating prism

A penta-prism can be used to turn a laser beam through a right angle even though the prism is not precisely aligned [17]. By rotating the prism about the axis of the incident beam, as illustrated in Fig 4, the output beam sweeps out a flat plane. Systems of this type are used on construction sites to align ceilings, walls and foundations. In many cases a HeNe laser is used, so that the scanning laser beam produces a red line on the object which can be viewed by the human observer in

order to align the object. If greater accuracy is required, or automated alignment desirable, a position detector can be used. By using a laser beam which scans out a horizontal plane, an automated position detector system can be used to detect the beam and control the blade on the earth moving equipment, so that an absolutely flat surface can be graded. Farmers and road builders use these systems to grade their fields.

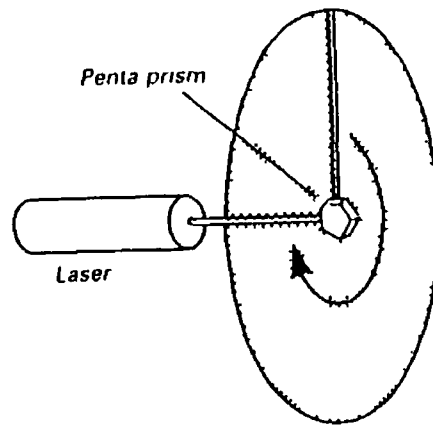


Fig 4 Penta-prism scanner [17]

Properties of Mechanical scanners

There are of course limitations to using mechanical deflectors which are summarised in the following points [18],[19]

- Scan speed - ms rates
- Complex design - expensive
- Susceptible to damage
- Limited life due to mechanically moving parts
- Suffers from 'wobble' (facet to facet pyramidal error)

Applications of Mechanical Scanners

Mechanical scanners are used when a large range of movement is needed and high speed is not necessary [20]. A common application of a scanner such as a

galvanometer mirror is for a laser light show. Laser light shows use the special properties of the laser beam to create visual displays on a large scale. The scanner is used to trace a pattern with the beam from a visible laser light on some surface like a screen or a wall. By scanning rapidly enough, the traced pattern appears to be one solid line. Effects can be enhanced by adding smoke or steam in the beam path so that it too can be seen. Many commercial companies offer laser light shows for concerts and as stand-alone events. There are several permanent light show displays in the country.

Scanning the beam of a high power laser on a surface can be used to engrave patterns on that surface. When the engraving only requires medium resolution on a small scale, a mechanical scanner can be used to position the beam. The scanner is often controlled by interfacing it with a computer that provides the appropriate current for each scanning position and allows the user to program individual position values or a model of the image to be engraved.

2.5.2 - Acousto-optic Deflectors

Many of the applications that employ lasers require the laser to be modulated and deflected. Acousto-optic devices are perhaps the most versatile means of incorporating information onto a laser beam. In order to understand acousto-optic deflectors we must first discuss modulators. Acousto-optic modulators are used for the production of short, high-power pulses from lasers, beam deflection, amplitude modulation and frequency modulation [21]. An acousto-optic modulator is a device that uses a transparent solid block of material, such as fused quartz, to which is attached a piezoelectric transducer. The acousto-optic effect is caused by sound waves in the crystal. If pressure is applied to the material it causes a change in the material's refractive index. If the applied pressure is varied sinusoidally, the changes in the refractive index will vary as well. In an acousto-optic device (Fig 5), high frequency pressure changes are created in a crystal by vibrating its surface with a transducer. The waves in the crystal produce an effect similar to a diffraction grating. Therefore, light passing through the crystal will be split into two or more parts (or

orders) the angle of the split beam and the intensity of each part can be controlled by controlling the frequency and amplitude of the sound waves. Scanners use the part of the beam that is split at an angle to the original

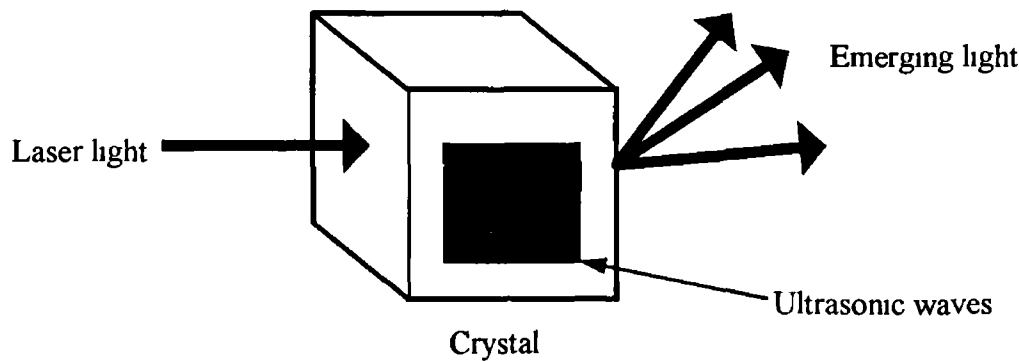


Fig 5 Diagram of Acousto-optic device

Consider Fig 6, an acousto-optic cell operating as a deflector [22]. The time bandwidth product is a measure of the acousto-optic resolution capability. Obviously this resolution can be translated to spots on a scan line by means of focusing optics. For high resolution one looks for a high bandwidth and long fill time (time for the sound to traverse the laser beam). This latter criterion requires the use of materials with acoustic velocities as low as possible.

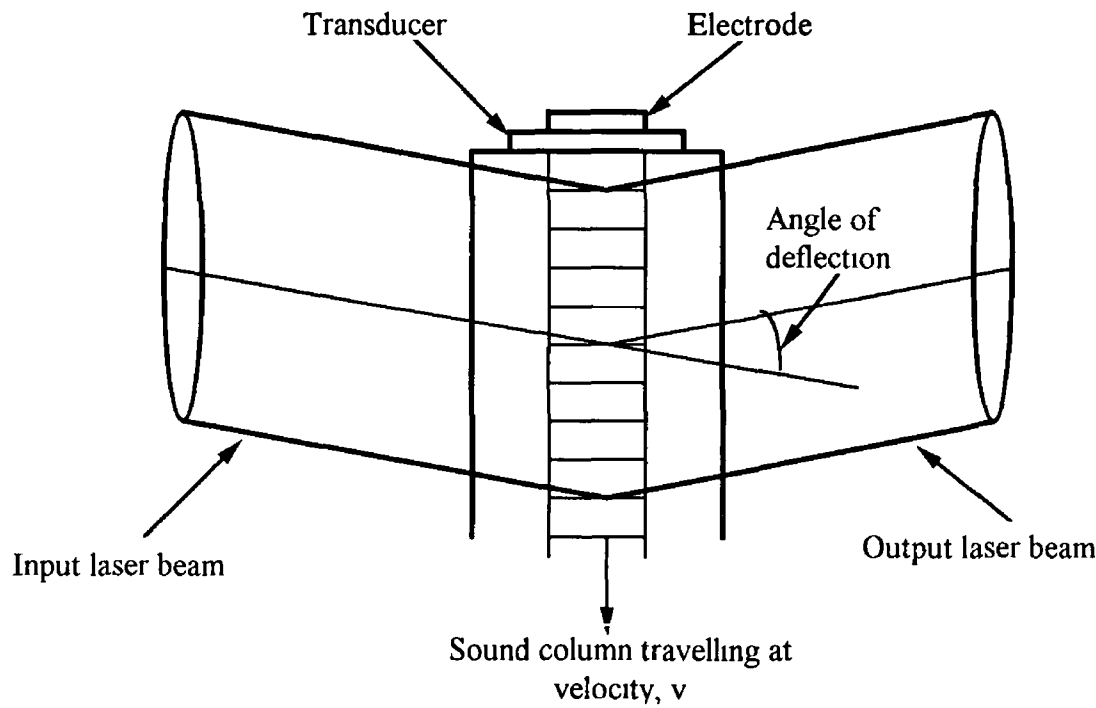


Fig 6 Acousto-optic cell operating as a deflector [22]

With acousto-optical scanners high deflection rates can be achieved, but due to the slow velocity of the acoustic wave (4.2 km/s on TeO₂ crystals) a very small spot (<30 μm) is needed to obtain fast rise and fall times (<5 ns). A high frequency (>200 MHz) acoustic wave must be generated in the crystal in order to obtain deflection or modulation which has to be switched on and off very rapidly. Expensive high frequency electronics are needed for this purpose. The fabrication technology of the acousto-optical scanners is complicated, a precisely elaborated ultrasonic transducer must be attached to the deflecting crystal. It is obvious that scanning systems fabricated with such scanners are complicated and very expensive.

Properties of Acousto-optic devices

- Scan speed < 100 μsecs
- Resolution up to 1000 spots per line maximum
- Scan angle typically < 3° in commercial devices
- To minimise loss of resolution $T(\text{flyback time}) \ll \text{scan time}$
- Upper limit on resolution depends on the highest acoustic frequency that can be used
- Maximum acoustic attenuation across the aperture = 33 dB

Practical problems with Acousto-optic devices

- Drive power limitations
- Thermal effects
- Difficulty fabricating high frequency transducers with wide bandwidths

2.5.3 - Electro-optic deflectors

The electro-optic effect found in some materials involves an interaction between an electric field and the polarisation of light [23]. In electro-optic materials, an applied electric field (voltage) will cause the material to become birefringent. This

birefringence splits light passing through the material into two parts that travel at different speeds. When the light emerges from the other side of the material, its two parts will be recombined to form light having different polarisation. As is shown in Fig 7, by carefully controlling the strength of the field and the size of the material, the electro-optic effect can be used to change the orientation of linearly polarised light.

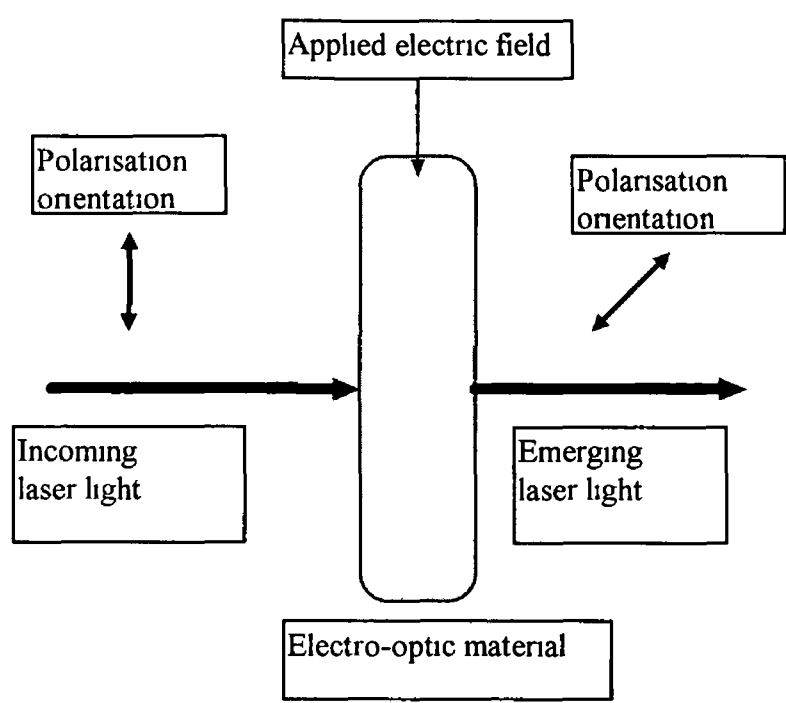


Fig 7 Electro-optic effect [23]

Electro-optical scanners have the capability to allow principally fast scanning, but at the present time the commercially available devices are bulky and expensive and need a high driving power. At present, a new novel electro-optical scanning device is being currently developed. Generally, these devices consist of prism arrays of alternating domain inverted and non-inverted prisms, i.e. with alternating direction of the C-axis of the electro-optical Crystal (e.g. Z-cut LiNbO₃ or LiTaO₃). The basic principle of the electro-optical deflector is shown in Fig 8. By applying an electric field to a metal electrode common to all prisms, refractive index changes of alternating sign ($+\Delta n$ & $-\Delta n$ resp.) are induced in every prism pair. The laser beam is refracted at the interfaces between corresponding prisms and can be deflected stepwise. Continuous

(analogue) deflection is obtained by adapting the phases of the portions of the refracted beam with additional electrodes in front of the prism. Because of well defined interfaces between the prisms superior beam quality can be expected. In a first step photolithographically well defined domain - inverted regions will be produced by domain inversion in LiNbO₃ (or in LiTaO₃). The inverted prisms are formed using a completely planar technology. There are several well established methods for producing domain inversion in LiNbO₃. To complete the deflection structure a common rectangular metal electrode is deposited in a second step, which produces a homogenous electric field.

The construction of scanning devices to be developed is much simpler than that of any comparable corresponding mechanical and acousto-optic deflector. They can be fabricated with a completely planar and cheap technology and need no parts to be attached, such as ultrasonic transducers which are expensive and difficult to handle. Electrically they are capacitors allowing high speed operation.

Electro-Optical Deflector Prism

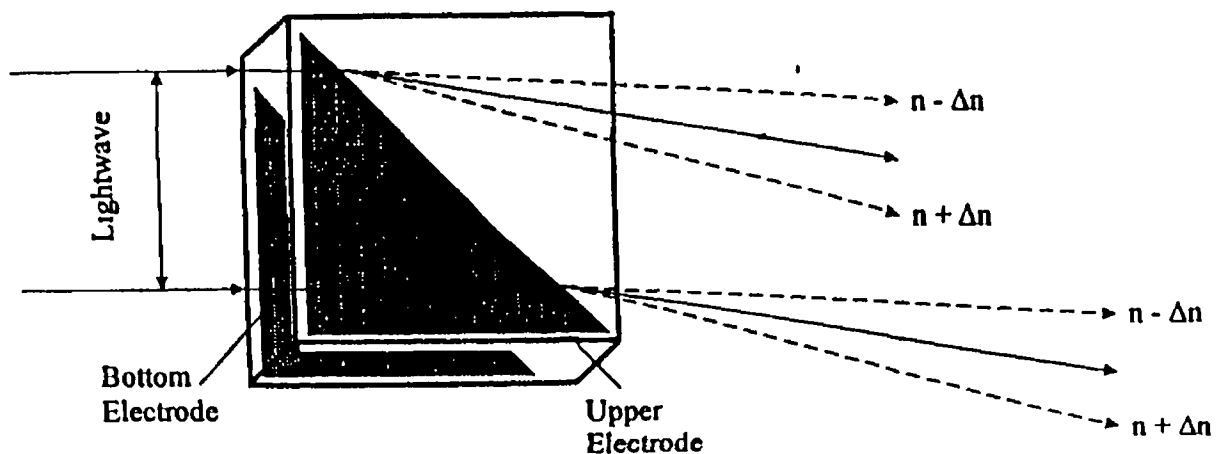


Fig 8 Electro-optical prism

Properties of the novel Electro-Optic deflector

- High deflection speed - nS rates achievable
- High resolution - more than 1000 resolvable points achievable
- Accurate deflection angle - construction dependent
- Easy to use in random access mode
- Simple driving circuits, no RF-power required
- Simple structure, simple planar technology
- No shift in the optical frequency
- High stability - no temperature compensation required
- Long life - solid-state device with no moving parts

Applications of the Electro-Optic deflector

- Read/write devices for optical memories
- Scanning devices for defect recognition and control
- Digital displays for alphanumeric and graphical data
- Real-time large screen or TV-displays
- Analogue-digital converters
- Switches
- Optical Radar
- Bar-code reader
- Laser-printer

2.6 - Surface Inspection

At a time of rapid development, introduction of new technologies and increasing world-wide competition, the quality specifications for products and materials are becoming ever more demanding [24] This also applies with regard to the avoidance

of defects in the surfaces of materials. Consequently there is a need for systems which allow 100% on-line testing of materials and surfaces during production [25]

Surfaces of industrial parts need to be specified based on their utility and application environment [26]. Surface characterisation is hence very vital for design, manufacturing and inspection. Current techniques of surface measurement use surface profilometers, coordinate measuring machines and some optical techniques to estimate the nature of surfaces. With the advent of automation surface characterisation needs to be totally computerised so that the task of surface inspection is greatly simplified [27].

Generally there are two methods of on-line inspection: contact and non-contact methods [28]. The majority of contact methods refer to the use of stylus based instruments. However it is well known that all surface metrology systems based on this technique suffer from a number of limitations [29].

- The stylus can damage the surface
- It can be damaged by the surface
- Care is needed when scanning in more than one direction, the lateral movement needed when raster scanning a surface can cause the stylus or cantilever to break or jump

Optical based non-contact methods of surface inspection hold the promise of faster data capture rates with none of the limitations of contact methods mentioned above. Any industrial systems that use Low-power lasers for alignment, gauging or inspection generally consist of four basic units [17].

- 1 Laser light source
- 2 Optical system to direct and structure the light
- 3 Optical system to collect or image the light after it has interacted with the object or medium being interrogated
- 4 Detection system

Much research in this project has gone into the applications of laser based inspection systems and many of these will be dealt with in the next section. The examples of inspection systems given are important to understand as they operate under many of the same principles as the system designed for this project.

2.7 - Laser Scanning Inspection Systems

Fig. 9 is a simplified diagram of a surface inspection system. In many systems, an oscillating or rotating mirror is placed at the focal point of a converging lens to produce a scanning laser beam which remains parallel to the lens axis. In Fig. 9 it is assumed that machined surface is smooth, except for the surface flaws which tend to be filled with black residue from the machining process. The laser beam is scanned across the machined surface. As the light scans the specular surface, it is reflected to a second converging lens and focused onto a detector. When the beam scans a flaw, the light is absorbed, and the amount of specular reflected light decreases. Thus in observing the reflected light with the detector, the light level will be high when the laser beam scans the smooth machined surface and low when it scans a flaw. The signal output from the detector can be evaluated by using the computer.

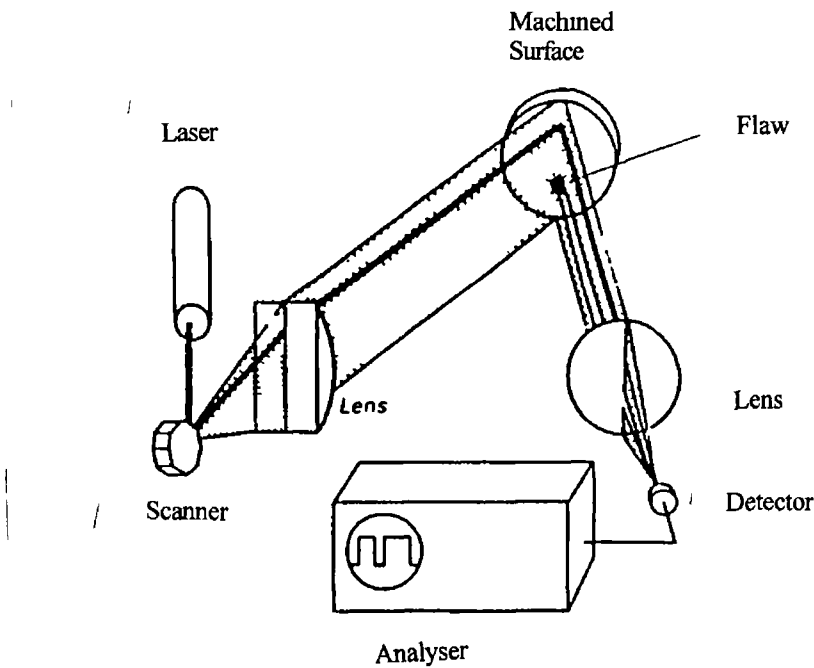


Fig 9 One-dimensional laser scanner flaw detector

Another technique that can be used is to observe the light scattered from the surface incorporates a detector placed to observe scattered light. This will detect very little light as the laser beam scans the specular surface, but will detect more light as the beam scans a flaw. This technique is particularly good for detecting scratches on an otherwise specular, mirror-like surface. To inspect entire surfaces, one technique is to move the object being inspected so that the entire surface is scanned. Another technique is to scan the laser beam in a raster pattern by using two rotating or oscillating mirrors. A two-mirror scanner system is shown in Fig. 10.

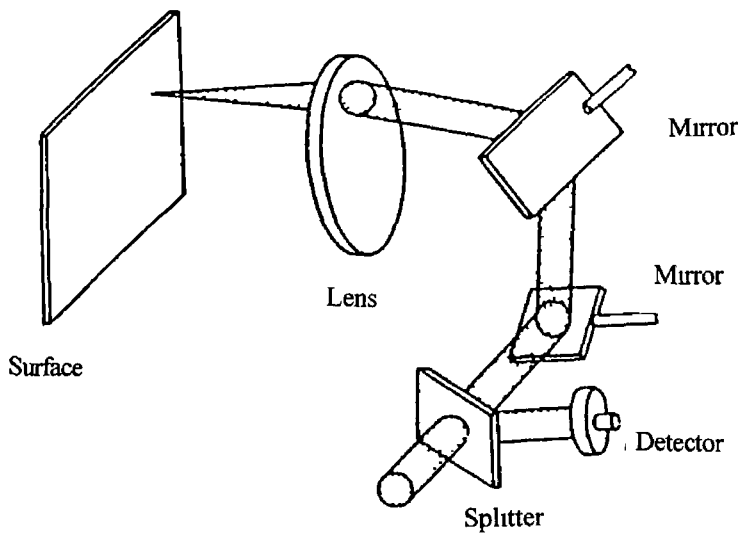


Fig. 10 Two-dimensional laser scanner flaw detector

Laser light is focused on the surface by a converging lens. One mirror rotates or oscillates rapidly to scan the beam in the horizontal direction, while the other rotates or oscillates more slowly to move the scan line vertically. In the system illustrated in Fig. 10, reflected light is received back through the converging lens and is then reflected by a beam splitter to a detector.

2 7 1 - Automatic surface inspection of continuously and batch annealed cold-rolled steel strip

The increasing demand for high surface quality in steel products, manufactured at high production speeds in cold rolling mills and surface finishing lines, requires new methods for optically controlling the surface condition. Prompt recognition of surface defects is an important prerequisite to insure high quality and optimal production control.

While inspecting web material at high speeds, an automatic surface inspection system, used in place of visual inspection, must be able to [30]

- Reliably find all surface defects, even small and low contrast flaws
- Reliably recognise defects at an inspection rate of up to 600 metres/min
- Locate defects on material with varying reflective properties
- Correlate the detected defect signals to defects on the material
- Differentiate defects according to type and size

An overview of the major components of this surface inspection system are shown in Fig 11. A laser beam produced by the scanner moves along the steel strip surface in a narrow line with a defined light spot at such a high speed that the entire surface is completely inspected. The laser light, which is either reflected or scattered by the material surface, is collected by two light guiding rods and converted into electrical signals. These signals are electronically conditioned and connected to the control signal of the scanner, so that the defect discriminator and system computer can process the information. Detected defect signals are displayed on a colour monitor according to their position and size. For logging the defects over larger web lengths, the defect signals are condensed and reported on a computer printout.

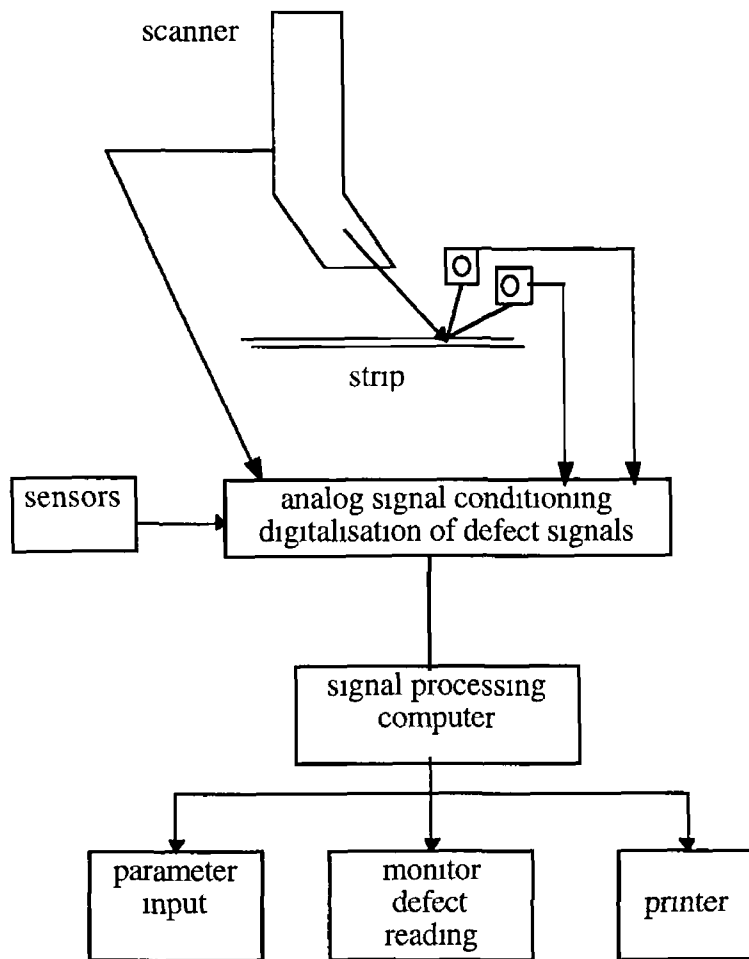


Fig 11 Surface inspection system [30]

A typical inspection report as displayed on the monitor is shown in Fig 12. The headline shows both the parameter set valid at inspection time and the current strip number. In the second line, the corresponding data for the next strip are displayed. The entire inspection width of 1600mm is subdivided into 16 inspection lanes, each of which is 100mm wide. In each of these lanes, defect information is displayed for channel 1 and 2. Included in Fig 12 are samples of most possible defect types along with their corresponding symbols. In addition to the compiled inspection data, the printed defect map includes reports regarding the condition of the entire inspection system.

actual strip-No 1234 parameter = 14
 preset strip-No 9876 parameter = 3

zone of inspection																	strip length
16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1		00002
□													*				00004
							◆										00006
										+							00008
							*										00010
			*							□							00012
							◆							♠			00014
											□			◆			00016
							*										00018
																	00020

*,+,◆,□,♠ - Types of optical defects

Fig 12 Typical inspection report on monitor [30]

2 7 2 - Quality Control technology for Compact Disc manufacturing

Defects can occur at any point in the production process of compact discs The consumer demands that the CD manufacturer brings a disc of outstanding quality to the market The CD manufacturer must have a final inspection process that will both detect these defects and help to remedy their causes Discs containing defects much smaller than the threshold of audibility must be rejected This preserves fidelity so that subsequent damage to the CD will not cause the manufacturing defects to become audible The ability to detect these defects rapidly with exact data and statistics significantly reduces the manufactured cost per saleable compact disc The SICK SC 60 compact disc inspection system has been developed and tested in cooperation with a major compact disc manufacturer for 100% inspection of all CD audio and CD ROM discs [31] Use of this system reduces manufacturing costs and reduces the risk of defective products slipping past the final inspection stage, which could undermine the manufacturer’s reputation in the market place In addition to providing production statistics, system outputs can be used to directly control parts of the production process itself

Each stage of CD production contributes unique defects which the inspection computer can characterise and statistically summarise. A brief catalogue of CD defects which must be detected include

- Damage to the information surface
- Damage to the surface on the read side
- Bubbles or inclusions in the substrate material
- Metalisation defects, either single or several minor defects within a small area

A CD inspection system must reliably detect all these type of defects, and it must be able to classify these defects and provide a measure of defect size. The inspection itself consists of three major components. An optical scanner, a receiver system and the electronic evaluation system. A block diagram of the complete system is shown in Fig 13

The optical scanner scans a fine point of light from a HeNe laser along the disc radius. As the disc is rotated, the entire disc is scanned. Laser light striking the surface at an angle to the disc is unsatisfactory. Internal reflection within the substrate may cause distortion of the size and position of the defects. The telecentric design of the scanner eliminates these problems by scanning normal to the disc surface along the entire radius of the disc. The receiver system is essential for recognising and classifying defects. The optical principle in the inspection of compact discs is based on the fact that various orders of diffracted laser light can be used in a selective receiver system. The electronic evaluation system is designed to achieve maximum flexibility as well as to rapidly process large amounts of data in order to inspect and classify the defects at a rate of one CD per second. The system creates a spatial raster of the CD in the direction of scanning, which is used to determine the size and location of defects. The defect classification matrix determines how electronic signals will be interpreted in order to classify the defect type.

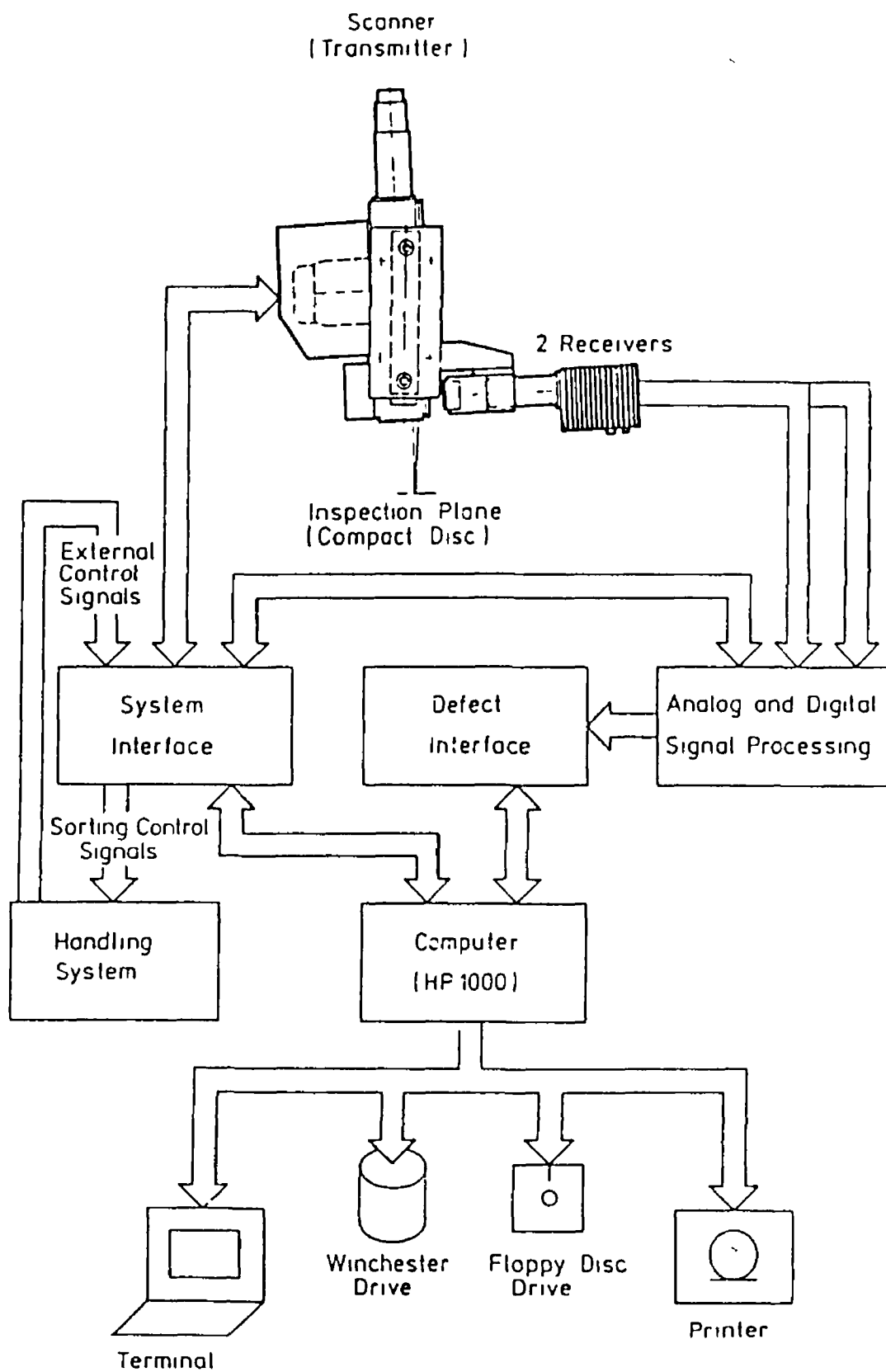


Fig 13 Block Diagram of CD Inspection System [31]

Defect information is stored on a 15 megabyte hard disk for production reports. The predefined reporting modes include current order, shift, and monthly reports. The defect statistics and system parameters are of special interest for the control and optimisation of the production process. The inspection computer may be linked to the plant computer via standard communication protocols. Thus the information from the inspection system may be linked to other types of plant information. In addition to the high speed production mode of operation, the system can also run in a special record mode. In this mode a detailed defect map is produced for each disc when it is inspected. The process engineer can verify proper operation of the system, or make minor adjustments to the sensitivity. This is a great aid to fine tune the system after a process change, or for quickly checking system performance for defect detection and defect classification using standard, defect containing test CD's.

2.7.3 - Other applications of laser scanning inspection systems

There are many other applications for laser based inspection systems. Some of these include

- Laser scanners in tunnel inspections [32]
- Optical inspection of female contact's defects for multipin printed circuit connectors [33]
- Monitor of dimensions in the extrusion of plastics [34]
- Characterisation of silicon surface defects by the laser scanning technique [35]
- Photographic film inspection [27]
- Internal cylinder bore inspection [36]
- Laser scanning microscopes [37]

CHAPTER THREE

CHAPTER THREE

3 - Design and development of the Inspection system

3.1 - Introduction

In this chapter the design and development of the system used in this project to carry out the experiments are reviewed. The first part of this chapter deals with an overview of the complete system. The purpose of this is to give an overall pictorial view of the system and then through the use of a block diagram describe generally how the system is controlled. The block diagram should also give an indication of the various pieces of equipment used in the process, and the function each fulfils. Finally, each item of equipment used is discussed in detail giving diagrams, specifications and explanations as how each item of equipment is operated to its optimum capability.

3.2 - Overview of system

Fig 14 and Fig 15 are photographs of both the system itself, and the type of sample plates used for measurements. However, from the block diagram (Fig 16) it can be seen that the complete system consists of sub-systems. They are, the sensor (measurement system), the plotter, and the software needed to control the system. Each of these pieces of equipment will be discussed in detail further on in this chapter. For the moment it is enough to describe the function they fulfil and how they interact together. As can be seen the automated operation of the rig comes from the PC terminal. From this point all the other major parts of the system can be operated. The plotter controls the movement of the sample plate and the plotter movement is controlled through the PC. Therefore, when the movement of the plotter is discussed at any point what is really being referred to is the movement of the sample plate. This movement is accomplished by either a written program or using AutoCAD. The operation of the sensor is mainly controlled by software loaded on the PC. Any lateral movement of the sensor must be done manually. However, all the movement

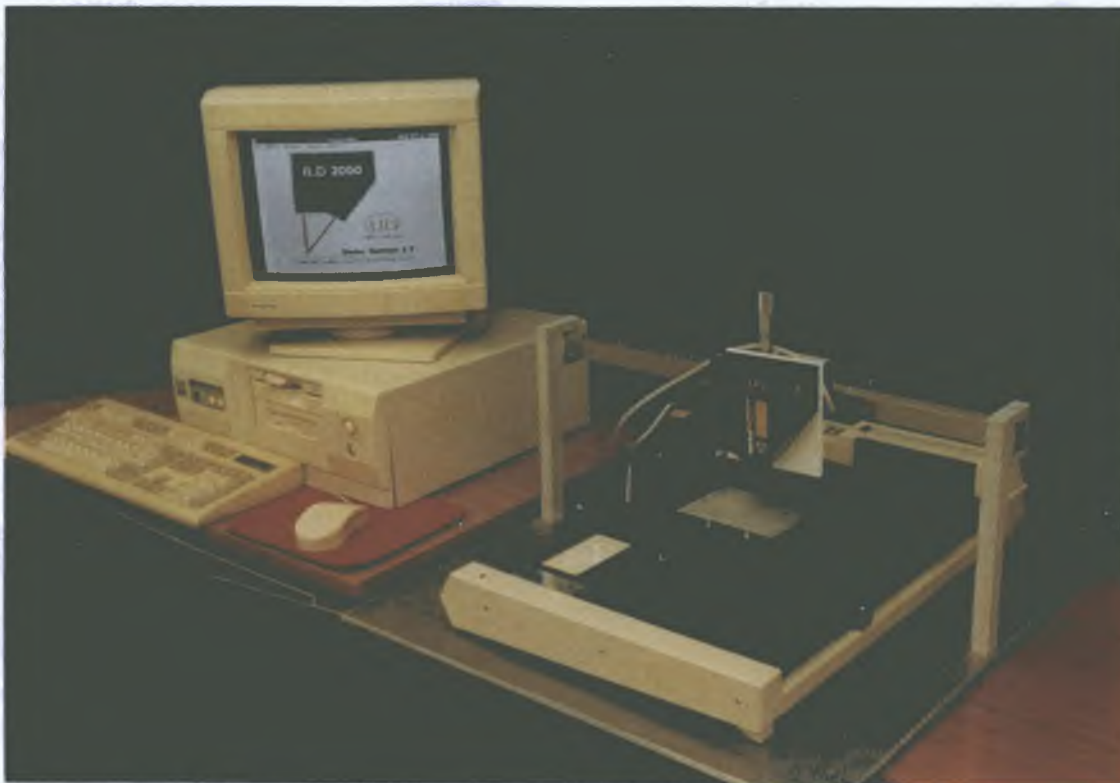


Fig 14. Photograph of the complete system in operation

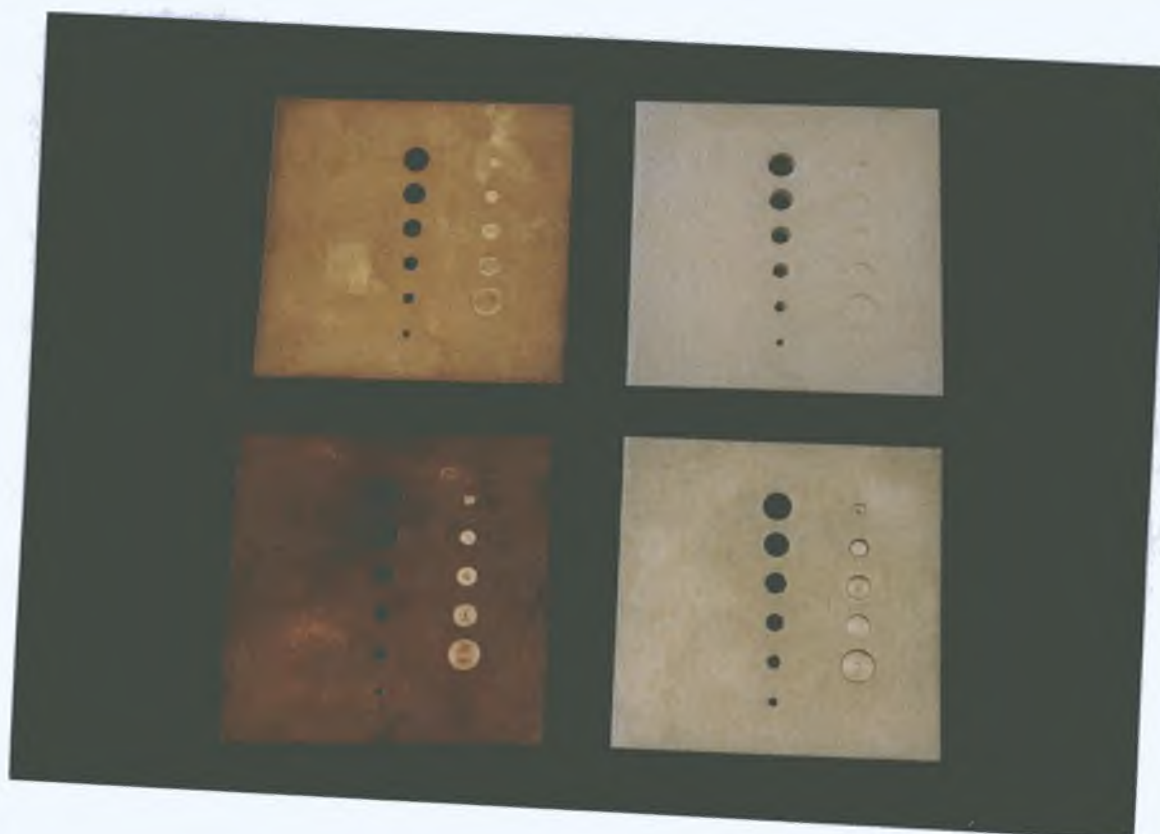


Fig 15. Selection of Brass, Copper, Polycarbonate and Stainless Steel sample plates

BLOCK DIAGRAM OF RIG

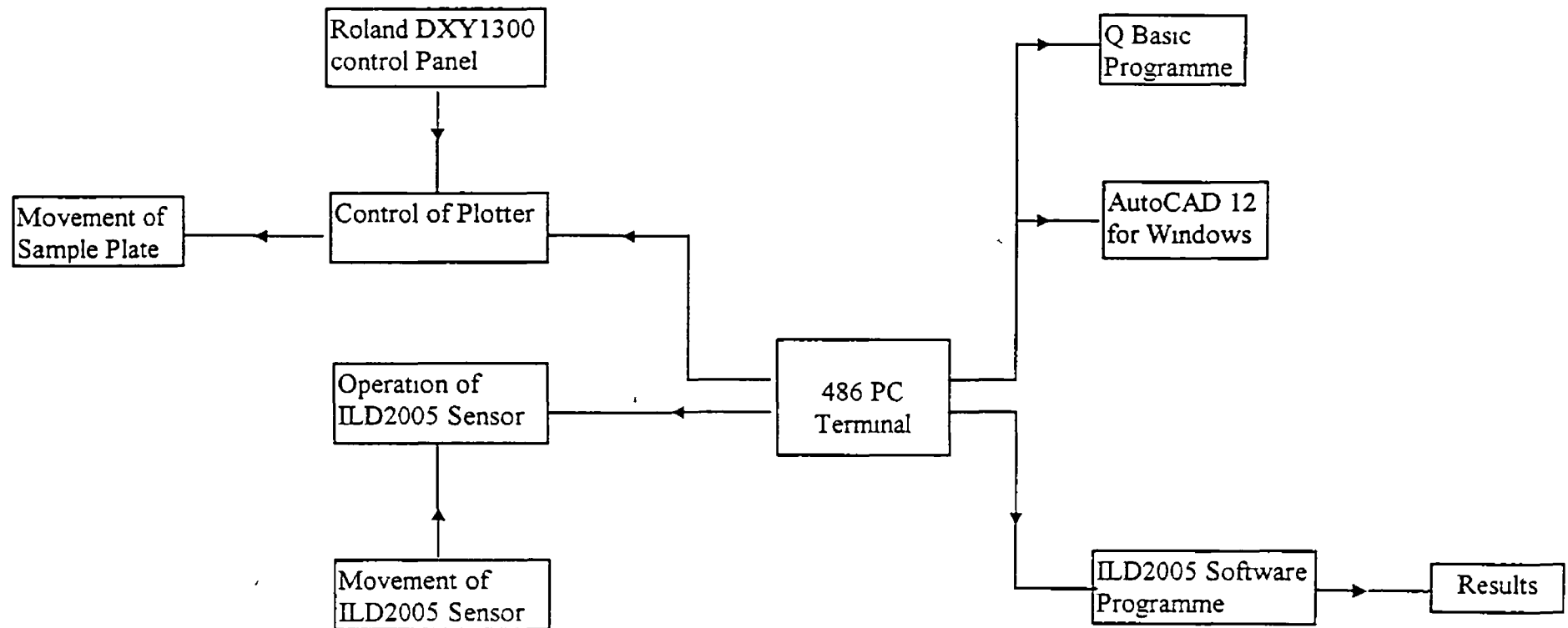


Fig 16 Block diagram of R₁g

we require for these experiments is done by the plotter Finally, all the output of results is saved and manipulated in the PC terminal

3 3 - Measuring system

There are two main options in the structure of the measuring system (Fig 17) In the first option (A1) the sensor is connected directly to a power supply unit that can give a read out of both the analog and digital signal In the second option (A2) the sensor is connected to a PC through an interface card As the digital signal is the one of most importance for this project the second option is the system used in this project However, preliminary tests were carried out using the first option in order to test the suitability of the sensor It is clear from Fig 16 there are three main hardware parts to the system Each of these parts will be discussed in turn

Structure of the Measuring System

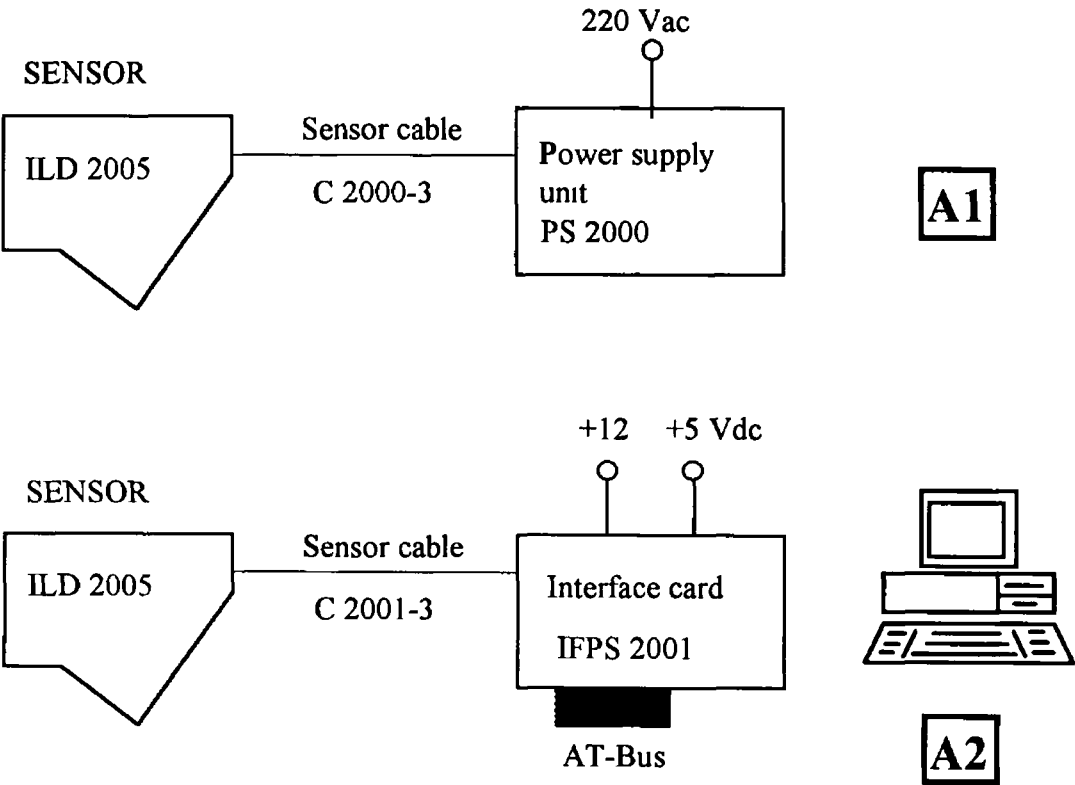


Fig 17 The two options for the structure of the measuring system

3.3.1 - Laser Sensor

The first and most important piece of hardware in the measuring system is the laser sensor itself. The type ILD-2000 sensor operates on the principle of optical triangulation. Fig 18 is a pictorial diagram of this sensor that gives a view of the various parts and operation of the sensor.

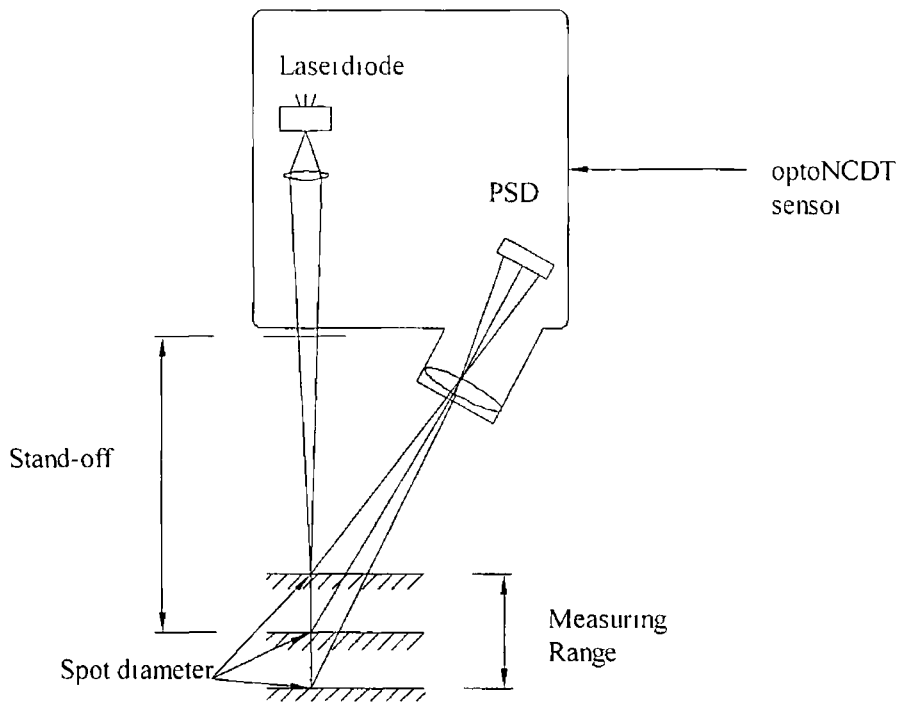


Fig 18 Diagram of Operation of optoNCDT sensor

From this it can be seen that a visible point of laser light is projected onto the surface of the target. The diffuse part of the reflection of this point of light is projected onto a CCD array by a receiving lens arranged at an angle to the optical axis. The intensity of the diffuse reflection is determined in real time from the CCD signal. This allows the sensor to stabilise fluctuations in intensity during measurement over a very wide reflection factor range (from almost total absorption to almost total reflection). A high degree of immunity from interference is achieved by early digitisation of the signal. The signal processing offers the possibility of adapting the sensor to material surfaces through the digital interface. This achieves a high

linearity even on weakly reflective materials (e.g. black rubber). The measured value is output simultaneously in analog ($\pm 5V$) and digital (RS485/687.5 kBaud) format. LEDs on the sensor signal "Out of Range" (upper and lower range values), a non-measurable target (reflection too low) "Poor Target" and Laser ON/OFF. A block diagram of the sensor can be seen in Fig 19.

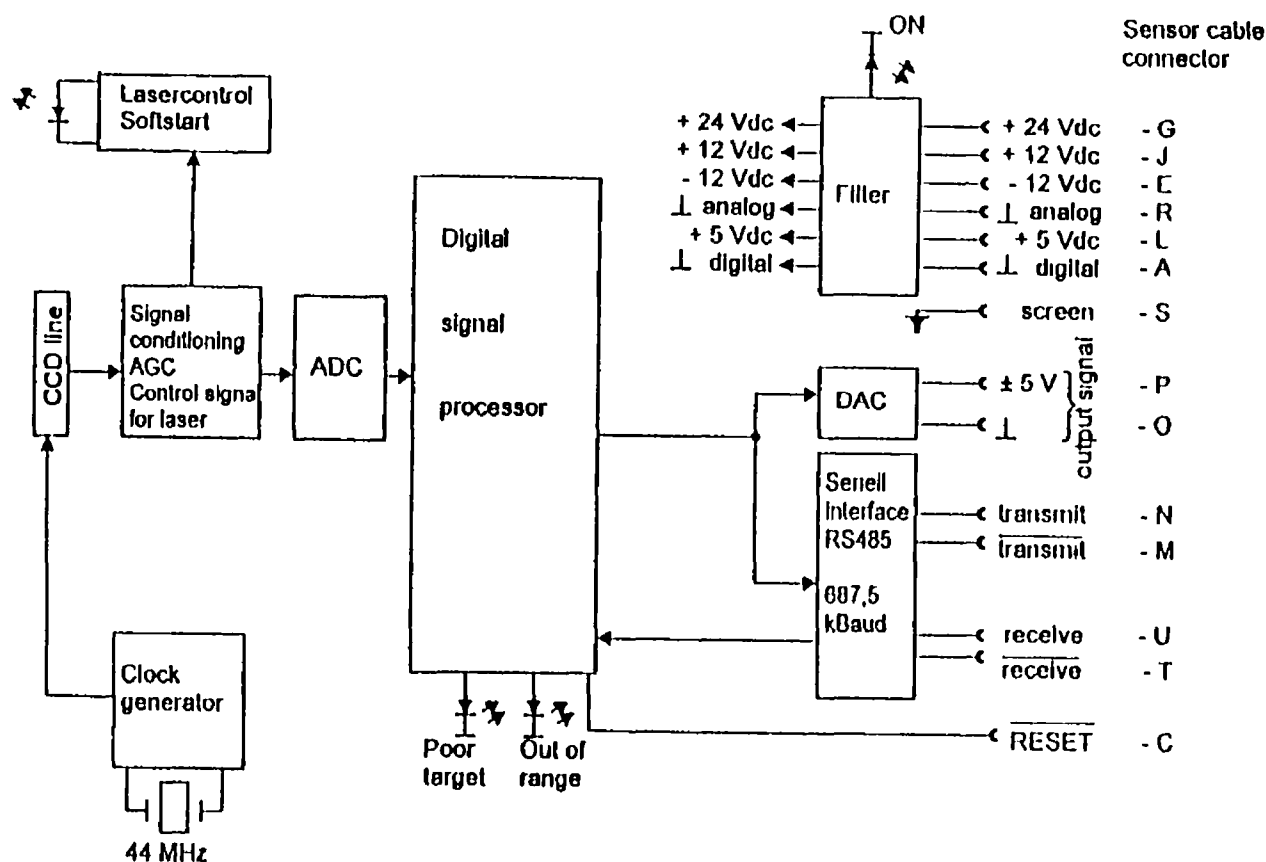


Fig 19 Block diagram of ILD 2005 sensor

In order to examine the capabilities and limitations of this sensor the following table gives its characteristics. After the table follows a description of influences that might cause an error in the output of the sensor and how to optimise the performance of the sensor.

Table 2 Specifications of the sensor

MODEL ILD2005 SENSOR	Specifications
Measuring Range	+/- 2.5mm
Stand off distance	58mm
Non Linearity 0.03% FSO	+/- 1.5 μ m
Resolution 0.005% FSO	0.25 μ m
Temperature stability	+/- 0.1 μ m/K
Light source	Semiconductor laser 670nm
Smallest light spot size SMR EMR	50 μ m 130 μ m
Sampling rate	10 kHz
Angle error at +/- 30° Tilting at the X or Y axis	typ +/- 0.5%
Angle error at +/- 15° Tilting at the X or Y axis	typ +/- 0.13%
Permissible incident light for direct radiation of a diffusely reflecting target	30,000 lx
Protection	IP 64 (with connected cable)
Operating temperature	0°C - 40°C (with free circulation)
Storage temperature	-20°C - 70°C
Output analog Digital	+/- 5V/R _L > 1 kOhm RS485/687.5 kBaud
Power supply through accessory power supply unit PS 2000 or Interface card IFPS 2001	4 supply voltages required +5 Vdc/500 mA, +12 Vdc/250 mA -12 Vdc/120 mA, +24 Vdc/30mA

3.3.1.1 - Triangulation Method

The most common technique used in laser inspection systems for defect recognition is the triangulation method. It is also the method used by the optoNCDT sensor in the system. Optical triangulation provides a non contact method of determining the displacement of a diffuse surface. Fig. 20 is a simplified diagram of a laser based system that is successfully used in many industrial applications. A low power HeNe or

diode laser projects a spot of light on a diffusive surface. A portion of the light is scattered from the surface and is imaged by a converging lens on a linear diode array or linear position detector. If the diffusive surface has a component of displacement parallel to the light incident on it from the laser, the spot of light on the surface will have a component of displacement parallel and perpendicular to the axis of the detector lens.

The component of displacement perpendicular to the axis causes a corresponding displacement of the image on a detector. The displacement of the image on the detector can be used to determine the displacement of the diffusive surface, thus any surface defect will give a different reading to that of the normal surface.

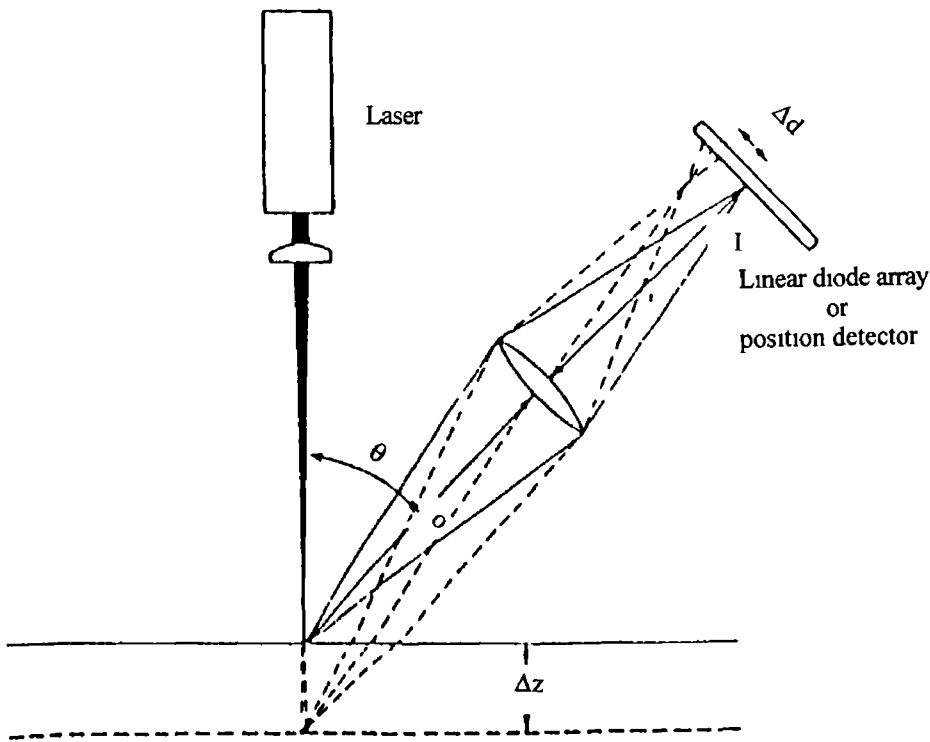


Fig 20 Diagram of laser based optical triangulation system

Many triangulation systems are built with the detector perpendicular to the axis of the detector lens, Fig 20. The displacement Δd of the image on the detector in terms of

the displacement of the diffusive surface Δz parallel to the incident beam (i) is approximately

$$\Delta d = \Delta z \cdot m \cdot \sin \theta \quad (1)$$

where $m=1/\sin \theta$ is the magnification factor and θ is the angle between a line normal to the surface and the light scattered to the imaging lens. Eqn (1) assumes the Δz is small and that θ remains constant as the surface is displaced. Thus we can use the approximate Eqn (1) to design an optical triangulation gauge, we cannot, however, assume that the equation is exact. After the gauge is built it must be calibrated by displacing a diffusive surface by known distances and determining the actual image displacement on the detector. A computer can be interfaced with the detector and programmed to determine the displacement of the diffusive surface from the displacement of the image on the detector.

Laser-based triangulation systems of this kind are extensively used in industry. One such application for such systems is to determine the level of molten metal in a pour box. By using an optical triangulation unit mounted on the arm of a robot, proper stand-off distance can be maintained so that the robot can perform operations such as welding and painting.

However, if a two dimensional measurement system is required using the laser-based triangulation method we must introduce the method of projecting the line of laser light onto a surface using a two-dimensional detector. With the introduction of computer vision into industry, systems of this type are now available from several vendors. The system illustrated in Fig 20 can make dimensional measurements in the x and z directions. To produce the laser light line on the part to be measured, a cylindrical lens is used. This lens extends the light in one direction, but not in the other. The Scheimpflug principle can be used to place the detector at the proper angle to maintain the best laser light line image focus on the detector. Note that the system is not designed to make measurements in the y direction. Triangulation devices of this type are used to make measurements of the depth and width of seams and gaps in sheet metal.

3 3 1 2 - Diffuse reflection technique

Real reflection is a combination of diffuse and direct reflection. In principle, the sensor detects the diffuse part of the reflected laser light (Fig 21). However, it is not possible to make a definitive statement on the minimum reflection factor because small diffuse parts can still be detected even from mirrored surfaces. This is done by determining the intensity of the diffuse reflection from the CCD array signal in real time and then stabilising the fluctuations in intensity. To use the sensor on transparent or reflective objects, manufacturer pre-testing is necessary.

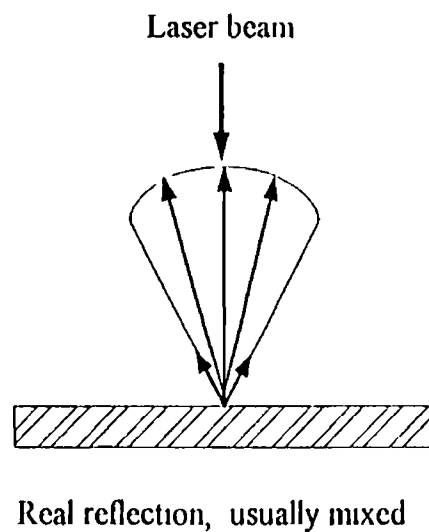
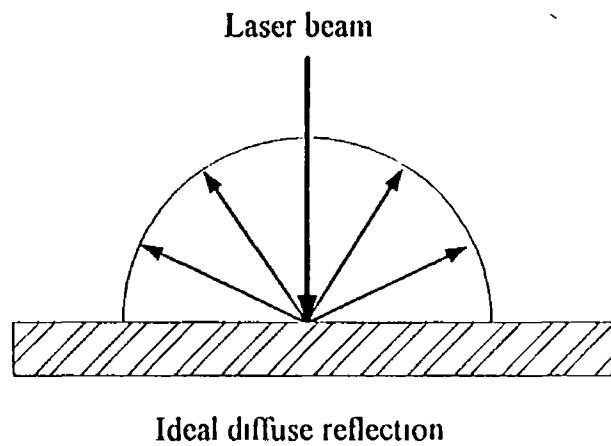


Fig 21 Principles of diffuse and real reflection

3 3 1 3 - Error Influences

Differences in Colour

Differences in the colour of targets effect the measuring result of the ILD 2000 only slightly due to the intensity adjustment. However, these differences in colour are often combined with different penetration depths of the laser light. Different penetration depths also cause apparent changes in the size of the measuring point. Therefore, changes in colour combination with changes in penetration depth can result into measuring errors. This phenomenon also effects the linearity behaviour of the sensor if it has been adapted to white diffusely reflecting reference material. If, on the other hand, the sensor is optimised for black material, a much better linearity behaviour is achieved.

Temperature Influences

The internal housing temperature of the sensor is measured by an integral temperature sensor and so the measured displacement values are temperature-compensated. A warm-up time of at least twenty minutes is necessary before taking data in order to achieve a uniform temperature distribution in the sensor. If measurements are to be made in the micron accuracy range the effect of the temperature fluctuations on the sensor must be considered. Fast temperature changes are damped by the sensors heat capacity.

Mechanical vibrations

If the sensor is to achieve resolutions in the micron to sub-micron range, particular attention must be paid to a stable or vibration-damped sensor and target installation.

Surface Roughness

Surface roughness of 5 micron and above create an apparent change in distance if the surface is scanned (also called surface noise). These can be suppressed by the technique of averaging.

Ambient light Influences

Due to the narrowband optical filter used, measurement can be made reliably even when a diffusely reflecting target is exposed to direct sunlight

Angle Influences (Fig 22)

Angles of tilt of the target around both the X and Y axis of less than 5° only causes errors with surfaces giving strong direct reflection. Angles of tilt between 5° and 15° cause an apparent change in distance of approx 0.1% of the measuring range. These influences must be noted particularly when scanning structured surfaces. In principle the angle behaviour is also subject to the reflectivity of the target surface.

Angle	X axis	Y axis
5°	0.04%	0.03%
15°	0.12%	0.1%
30°	0.5%	0.5%

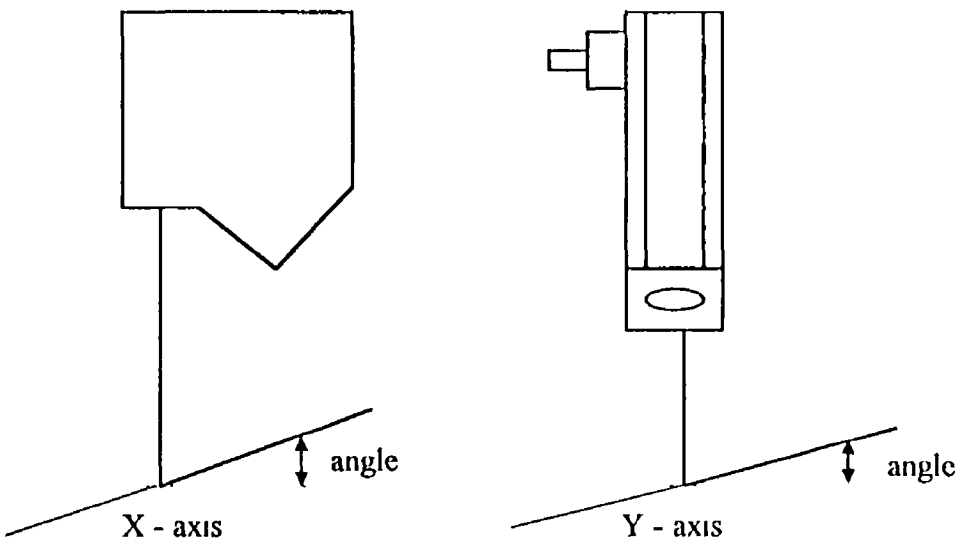


Fig 22 Angle Influences

Optimisation of the measuring accuracy by special sensor arrangement

In the case of rolled or polished metals moving past the sensor, the sensor plane must be orientated parallel to the direction of the rolling or grinding marks. The same arrangement should be made for coloured stripes (Fig 23)

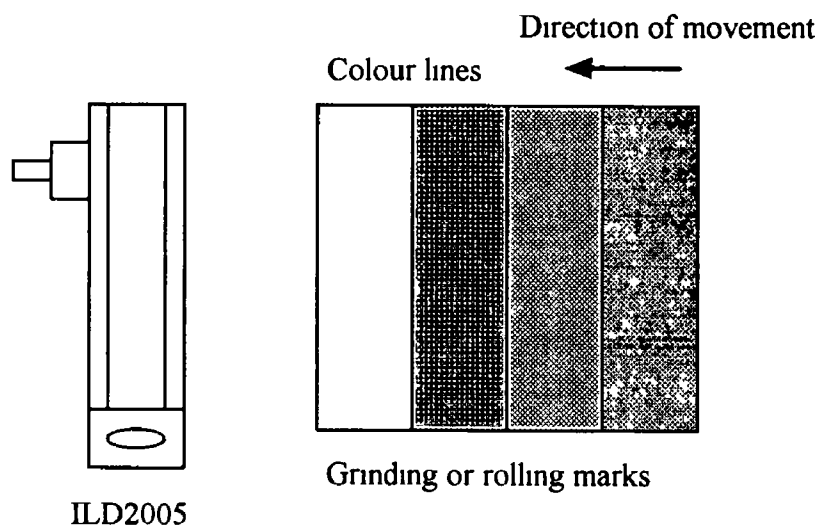


Fig 23 Sensor arrangement for ground or striped surfaces

In the case of drilled holes, recesses and ridges in the surface of a moving target, the sensor must be arranged so that the edges of these features do not obscure the backscattered light (Fig 24)

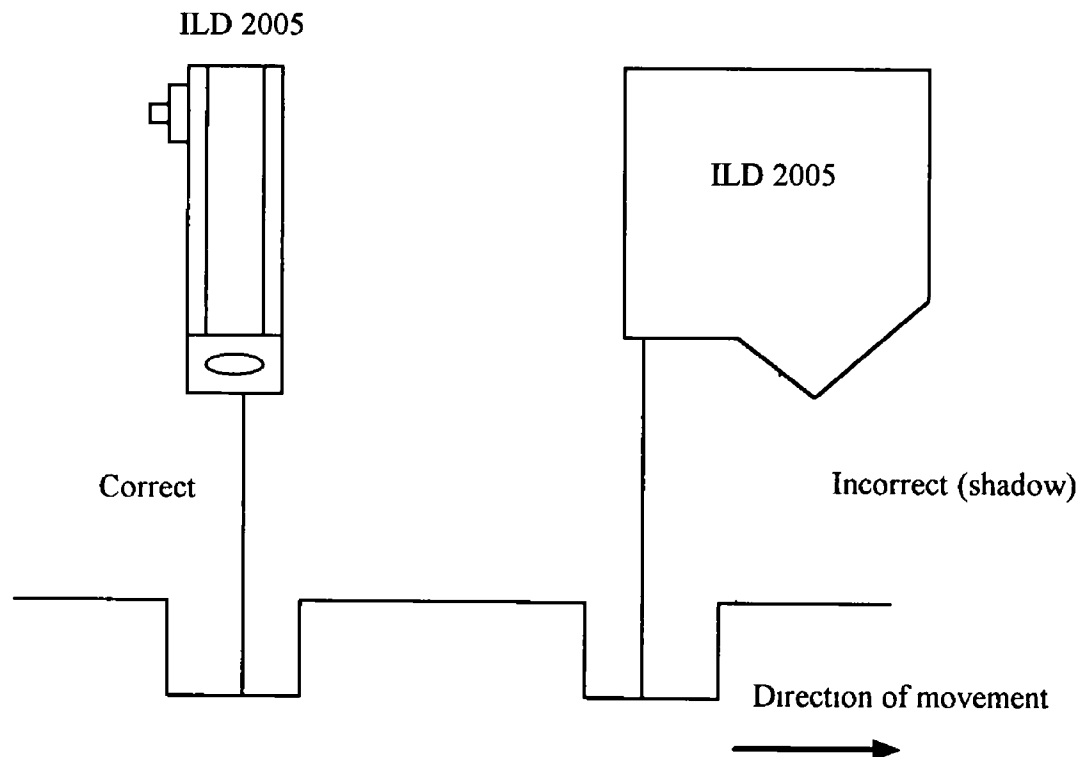


Fig 24 Sensor orientation for holes and ridges

3.3.2 - Power Supply Unit PS 2000

The PS 2000 power supply unit provides the voltages necessary for operating a maximum of two types ILD 2000 sensors. This power supply unit was used in the initial experimental stages to examine the analog output. The output signal is given as a voltage in the +/- 5V range at the two analog outputs. There is the possibility, if needed, of connecting up the unit to an interface card in order to examine the digital signal. A block diagram of this power supply with some of its technical data can be seen on the following page in Fig 25

3.3.3 - Interface Card IFPS 2001

This card provides one RS485/687 5 kBaud interface. It has an integrated power supply for operating an ILD 2000 sensor. The sensor and the card are connected by means of the C2001-3 sensor cable. The power supply and thus the sensor is switched on or off and the data transfer is carried out by the software or program modules. A diagram showing the layout of this interface card can be seen below in Fig 26

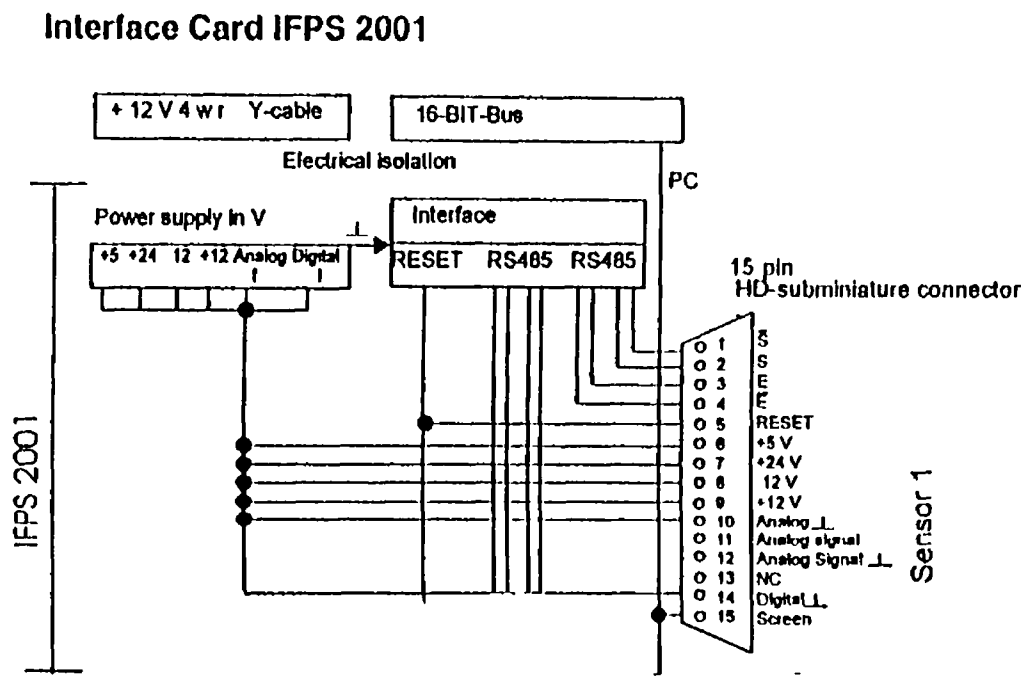


Fig 26 Block diagram of Interface card IFPS 2001

Block Diagram - Power Supply Unit PS 2000

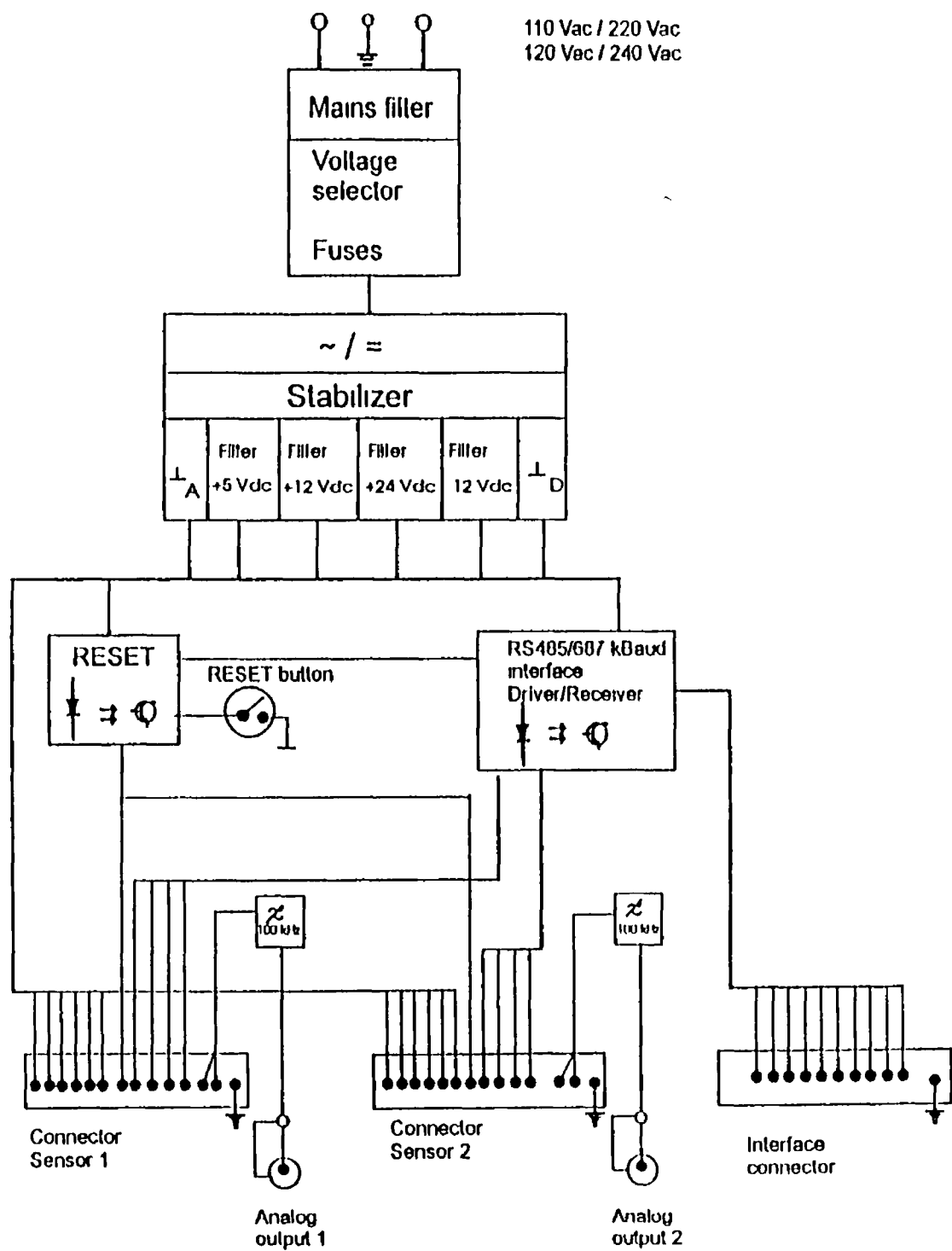


Fig 25 Block diagram of Power supply unit PS 2000

3 3 4 - Measured value output

Analog

After putting the sensor into operation, the displacement signal is available as an analog voltage value in the range +/- 5V

- the sensor output may only be loaded with $R_L > 1 \text{ k}\Omega$
- this analog signal is filtered through a 100 kHz low pass filter at the output of the power supply unit PS 2000
- the output has internal resistance of $R_i = 250 \text{ }\Omega$
- the error is 1.3 mV at the end of the measuring range at a load resistance of $R_L = 1 \text{ M}\Omega$

Digital

After putting the sensor into operation, the averaged value is available at the output of the serial interface in the range 0 - 65535

- 0 - 1637 - measuring value out of range (*)
- 1638 - 63896 - measuring value in the range (*)
- 63897 - 65534 - measuring value out of range
- 65535 >> Poor Target << - no range

(*) Both measured values no longer correspond to the sensor specification. They are used for adjustment in order to slightly exceed or drop below the measured value

An example of the signal output given from the sensor can be seen in Table 3

Table 3 Signal output of the sensor

Description	LED on the sensor	Analog output	Serial Interface
Laser in operation	Green -Laser On/Off		
Target does not reflect sufficiently Penetration depth of the laser point too deep - corona formation too great	Red - Poor Target	output > +5 26V or last valid measure	output 65535
Target still in detection range but slightly beyond the measuring range	Red - Out Of Range	output -5 00 -5 26V or +5 00 +5 26V	output 0 1637 or 63897 65534
No target available	Red - Poor Target Red - Out Of Range	output > +5 26V or last valid measured value	output 65535

3 4 - X-Y kinematics system

The objective of this system is to facilitate the movement of the sample being measured. It should fulfil the role of an X-Y table system. In effect we wish to be able to manipulate the sample plate in the X and Y direction using a scanning motion. This eliminates the requirement to move the sensor itself, thus simplifying the kinematics.

3 4 1 - Roland DXY 1300 plotter

This piece of equipment was used to achieve the required movement in the X-Y plane. All aspects on the operation of this equipment, and how it controls the sample plate, will be discussed in the following sections. One extremely important point of note is that the sample plate is mounted directly onto the pen carriage of the plotter. Therefore, any discussion of the movement of the pen carriage is in effect referring also to concurrent movement of the sample plate. Fig 27 gives two separate views of the plotter.

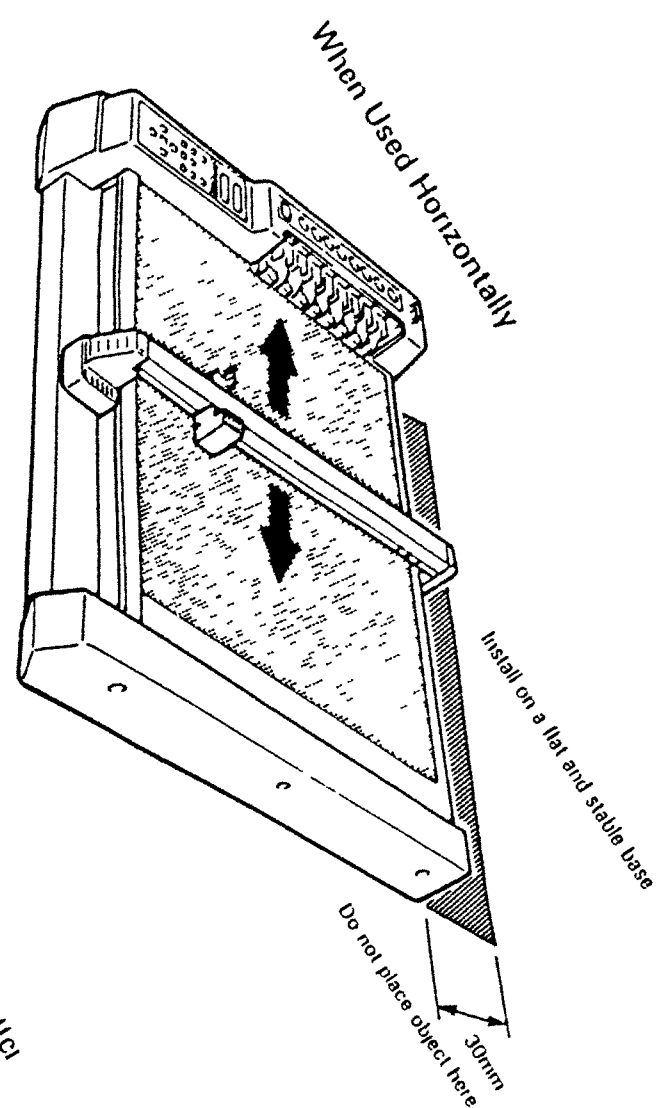
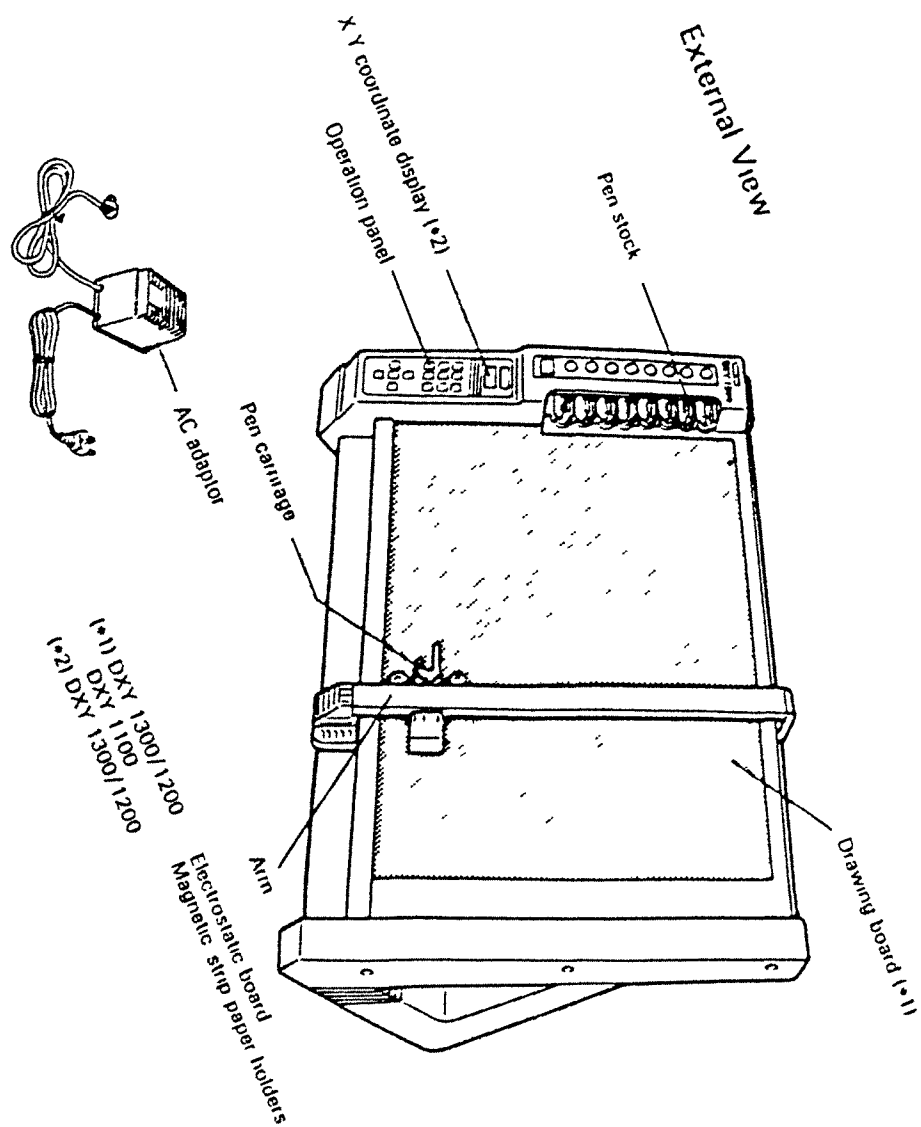
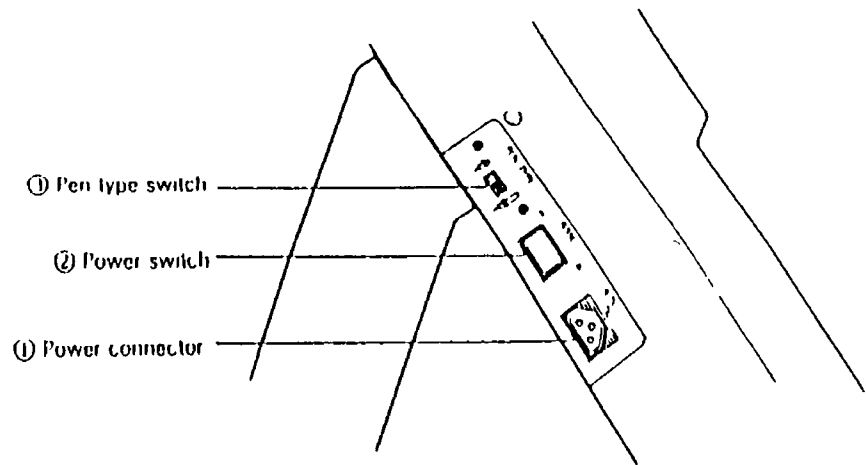


Fig 27 Two isometric views of the plotter



Having obtained an overall idea of the shape and movement of the plotter it is important to see the main features of the plotter Fig 28 gives a side view and a look at the rear panel of the plotter A description of the operational features can be seen in Appendix A

Side View



Rear Panel

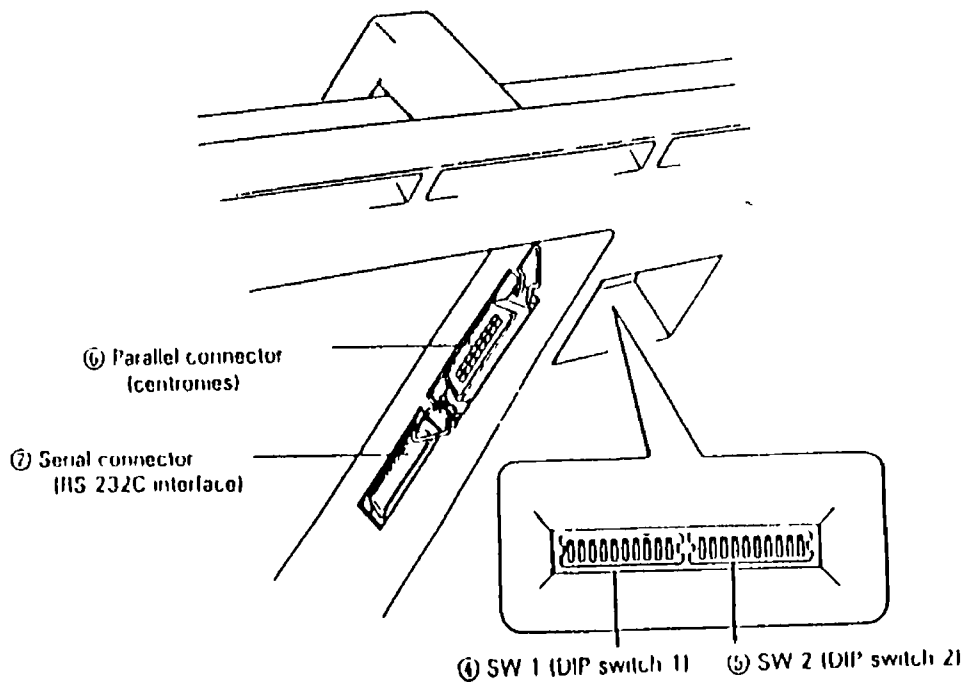


Fig 28 Some of the main operational functions

3 4 2 - Automatic control of the plotter

There are two separate methods for controlling the plotter other than its manual controls. They consist of either plotting a drawing from AutoCAD or by direct programming of the plotter using a program written under BASIC. The operations used for each of these methods will be discussed in detail giving emphasis to the particular solutions used for this project.

3 4 2 1 - Control by AutoCAD

As has been mentioned previously, the sample plate to be measured is connected directly to the plotter pen carriage. So when a drawing is sent to the plotter the sample plate moves in unison with the carriage. The sensor is mounted above the plotter drawing board at an arbitrary static position. When the sensor is switched on a red beam of light strikes the plotter below. Therefore, the motion of the plotter represents the scanning motion of an X-Y table. The X-Y coordinate display on the plotter control panel gives the coordinates of the plate at any moment in time. Therefore, using these pieces of information it enabled the calibration of plotting a drawing from AutoCAD to coincide with any particular area of the plate we wish to scan. The easiest way to illustrate this is by means of a typical example.

An example of a typical sample plate is given below in Fig. 29.

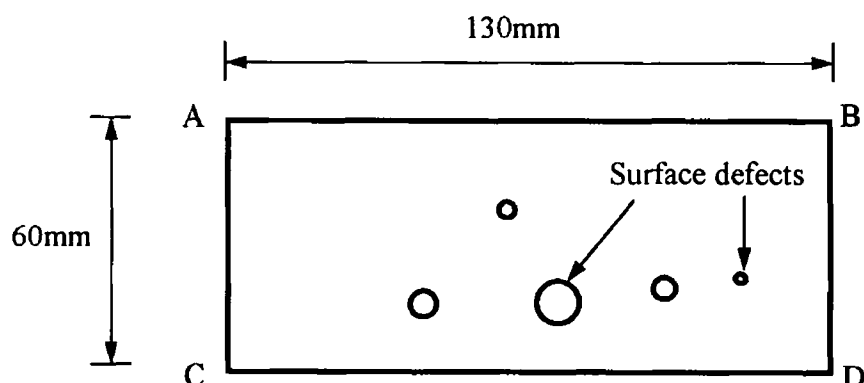


Fig 29 Diagram of sample plate

The dimensions of the plate are 130x60mm and there are surface defects of different shapes and sizes placed randomly throughout the plate. For the purpose of this project we wish to be able to scan the surface starting at point A and finishing at point D. The most economic way to achieve this is to scan in straight lines. The first line is from point A to point B. Then a step down is taken a certain distance and the second scan line begun in the opposite direction to the first. This process is repeated until it finishes with the last line from C to D. The step size moved down each time is predetermined depending on certain parameters (eg size of smallest defect, specifications of plotter etc.)

An example of a drawing plotted from AutoCAD to achieve this purpose is given below in Fig 30

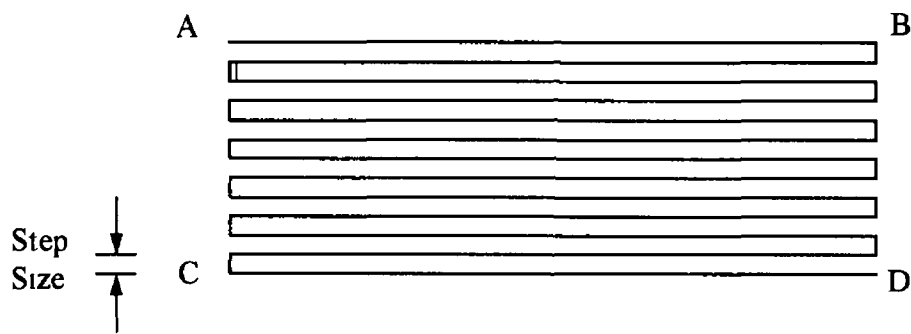


Fig 30 Plotted AutoCAD drawing

Plotting this drawing achieves the purpose of scanning the sample plate as described above. The location of the points A, B, C and D coincide with the same points from the edges of the plate (Fig 30). The method of achieving this end is described at the start of this section. Once the points A to D have been located the only other task is to specify a step size. The main consideration for this problem is to assure that the steps are small enough so as not to miss any of the defects. For this either need prior knowledge of what size defect is being sought, or a cut off criterion as to the minimum size defects permissible. It should also be noted that a knowledge of certain drawing parameters is crucial to assure the accuracy of the plotted drawing. For example when the drawing is plotted we must know what scale the drawing is in relation to real (mm) units.

3 4 2 2 - Formula for calculation of scanning parameters

- L - Total length of the scan line (mm)
- P - Plotter speed (mm/s)
- T - Total time for entire scan (secs)
- S - Sampling rate of sensor (Hz)
- V - Total number of values to be measured

In order to calculate [L] we need to know three measurements They are step size, scan length and the total number of steps taken (Fig 30)

$$L = (\text{Length CD} \times \text{Number of steps}) + (\text{Step size} \times \text{Number of steps})$$

Once we have calculated L and set the value for P we can calculate T

$$L \text{ (mm)} / P \text{ (mm/sec)} = T \text{ (secs)}$$

Having calculated T and set the value for S then we can calculate V

$$T \text{ (secs)} \times S \text{ (Hz)} = V$$

There are two main advantages of using AutoCAD for moving the plotter The first of these is the ease with which we can change the step size of the line scan As stated above once we know the location of the perimeter points A to D we can easily change the step size in the drawing to suit our needs The second advantage is the ability to change the pen speed/scan speed for different experiments In fact AutoCAD possesses the ability to vary the speed in forty two different steps from 14mm/sec up to 420mm/sec In order to do this all that is required is to change the pen speed assignments before sending the drawing to the plotter However these actual speed values had to be worked out manually using a ruler and a stop watch A full list of the actual speeds of each pen is given below

Table 4 Pen speeds available using AutoCAD

Pen No	1	2	10	20	30	42
Pen speed (mm/sec)	14	20	100	200	300	420

3 4 2 3 - Control through command system

This is the second method we have for controlling the plotter through the computer. The DXY 1300 series comes with two internal command systems: DXY-GL and RD-GL I. The plotter can be used by selecting either of them. The DXY-GL and RD-GL I commands have the following characteristics:

DXY-GL Commands

- There are 22 types of command
- Each command executes completely without the need of others
- They make the creation of programs quite easy
- They are compatible with Roland DG's DXY plotter commands
- They have a certain degree of compatibility with Roland DG's CAMM-GL I command system for the CAMM-3 modelling machine and CAMM-GL II command system for the CAMM-2 engraving machine
- They can call RD-GL I commands into use

RD-GL I Commands

- There are 56 types of command
- Several commands must be combined to execute one action
- They make programming somewhat difficult
- They permit high definition
- They are compatible with Roland DG's RD-GL plotter commands

3 5 - Software

The function of this software is to make it possible to take measurements using the sensor ILD 2005 under WINDOWS. This program was written for propagating the use of the sensor but it was not used in processing or data acquisition systems. There are certain limitations in measuring parameters by running the package under WINDOWS.

- The maximal sampling rate under WINDOWS is 1kHz
- The minimum sampling rate is now 1Hz
- The number of data elements is limited to 8000

3 5 1 - Software Configuration

From the software package written by Micro-epsilon (Germany), there are five separate menu headings to choose from. Each of these headings in turn has a few different possibilities. In order to understand how to work this software package the first step is to explain what each heading does. A full explanation of this package can be seen in Appendix B. Having explained the terms in Appendix B, an example of the measuring process for both continuous measurement and spontaneous measurement will be described.

3 5 2 - Sample measurement process

Before running an experiment it is necessary to set certain conditions or options. First we select the sensor type being used. In this case it is the ILD 2005, this indicates a measuring range of 5mm. Then there are a series of options. The first option is whether to acquire the data in decimal form or with the use of a comma. It is usually set to decimal form as this makes it easier to manipulate the data later. Secondly a TRIGGER can be set as to when to start the measurement. This enables the user to control the start of the measuring process. Finally there are the options of changing

the frequency limit or the number of averages for each measurement. Once all of these have been set the power can be turned on and the sensor is ready for operation.

There are two ways in which measurements can be obtained. They are single measurement or continuous measurement. For single measurement each time the return key is pressed on the keyboard the program records the value being measured at that point. This method is useful at the initial stages of measuring, or if there is a long discontinuity in parts where we require data. However, this can become a tedious process and is not very useful if it is not known where the defects are in the sample. Obviously a method of continuous measurement is much more desirable. Before starting the continuous measurement process it is necessary to define the total number of measurements to be recorded and the sampling rate. The total sample size must be between 100 and 8000, and the sampling rate must be between 1Hz and 1kHz. These limits, as discussed earlier, are determined by the limitations associated with running the sensor under WINDOWS. The total number of measurements, and the preselected sampling rate, will determine the duration of the measurement. The computer will acoustically signal the end of the measurement. After the measurement is complete the data can all be saved to a file. This file can then be brought into any other WINDOWS applications for further analysis. There is also a facility to graph and display various statistical data the data in the Windemo program.

CHAPTER FOUR

CHAPTER FOUR

4 - Experimental results and Discussion

4.1 - Introduction

This chapter deals with the various experiments that were carried out on the system and discusses the significance of the results obtained. The chapter can be divided into various different sections. Firstly, the initial tests carried out on the system measured the analog output tested on an aluminium plate. These experiments were important in deciding on the suitability of the sensor as a measuring device. The following sections deal only with the digital output. Each section will deal with the experimental results for each different material used. These materials will range from aluminium, stainless steel, brass and copper through to polycarbonate and perspex. Also, each section contains detailed graphs of the results obtained. These graphs will be discussed and explained thoroughly as to their significance and meaning. The first section of digital results on aluminium contains a detailed example as to how the graphs are obtained from the output information as well as a close look at the output information itself. The methods discussed in this section for manipulating the output information hold true for all the other experimental results.

4.2 - Analog tests

An example of the aluminium plate used for these experiments is shown in Fig 31.

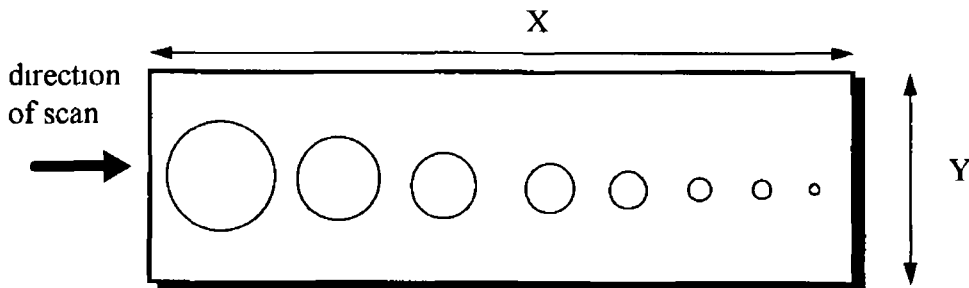


Fig 31 Sample aluminium plate used in analog experiments

As we can see from Fig 31 The sample plate consists of a piece of aluminium with eight separate holes The diameter of these holes varies from 25mm to 2mm respectively The average thickness of the plate was approximately 2mm However the plate had a slight curve in it so as it would not lie evenly on a flat surface The sensor remained stationary above the plate as the plate was moved underneath it in the direction indicated It was during this movement of the plate that the measurements were taken

The main objective of this exercise was to observe how the sensor reacted to surface defects and how it coped with different degrees of reflectivity of the surface type The analog output from the sensor is in the range +/- 5V and the sensor has a measuring range of +/- 2.5mm A typical measured output for the experiment is given in Table 5 below

Table 5. Analog output for aluminium plate

Hole Diameter (mm)	A (Volts) [Before]	B (V) [Across]]	C (V) [After]
25	0.004	4.54	0.692
20	-0.9	3.74	-0.9
17.5	-0.9	4.48	-0.78
15	-0.78	4.138	-0.68
10	-0.62	4.152	-0.454
7.5	-0.424	4.344	-0.2
4	-0.066	4.176	-0.06

The scanning across each defect is represented by the measured output analog voltages at A,B and C Where A is measured just before a defect, B is measured across the defect itself, and C is the measurement just after passing the defect The results of the analog test can be displayed as a 2D graph (Fig 32) This graph shows the sensitivity of the sensor The voltage can range from -5V to +5V It represents the sensors measuring range of +/- 2.5mm

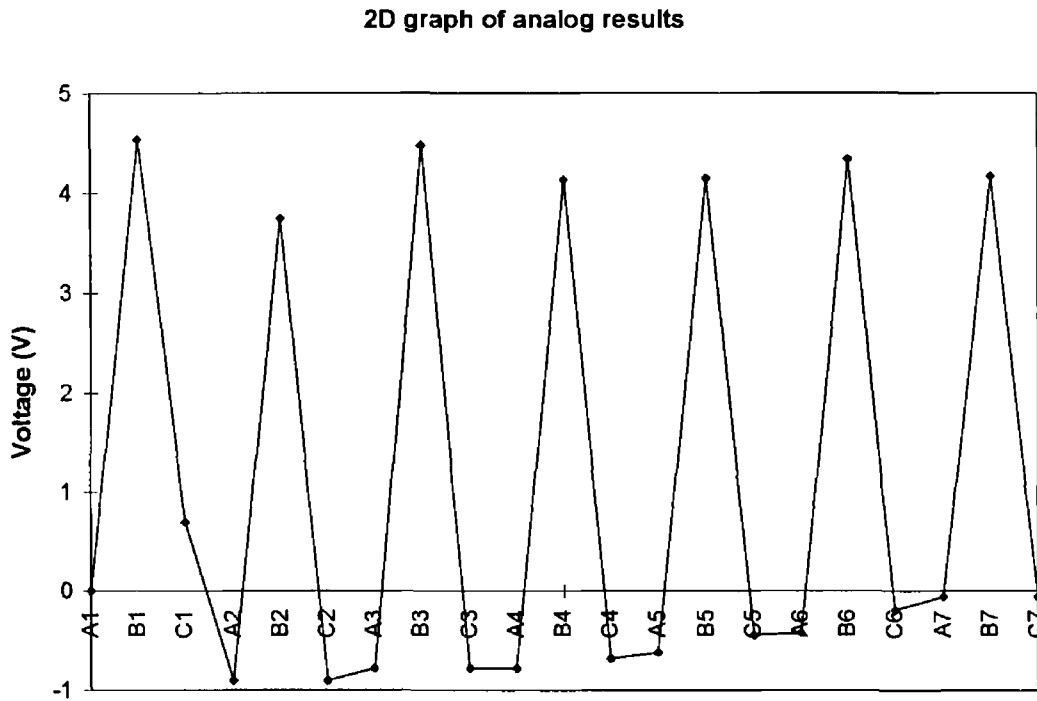


Fig 32 2D Graph of Analog test results on Aluminium plate

Each of the seven peaks that appear in the graph indicate the sensor's ability to detect each of the seven different size defects. This simple experiment was used to assess the sensors' ability to detect surface defects. Having been satisfied that the sensor has a suitable measuring range and capability, the next set of experiments to be performed were the digital experiments.

4 3 - Aluminium digital tests

4 3 1 - Selection of initial measuring parameters

This is the first experiment to be carried out when the entire system was up and running automatically. As such a detailed analysis of the entire measuring process, as well as the results, will be presented. The aluminium sample plate had dimensions 100x120x2.5mm. It was mounted on the pen carriage of the plotter (Section 3 4 1). The surface defects consisted of four separate holes with diameters 2,3,4 and 5mm respectively. It was decided to only scan an area of 79x75mm because all the defects were inside this area.

The next step before starting the measuring process is to determine certain measuring parameters. Once the scan area had been determined then an appropriate drawing in AutoCAD was plotted to accommodate this scanning area (Fig 33). For the initial testing a step size of 5mm was used. Therefore, fifteen steps (15x5) were necessary to accommodate the Y direction of 75mm. The coordinates for the edge of the plate were made to coincide with the start of the scanning pattern.

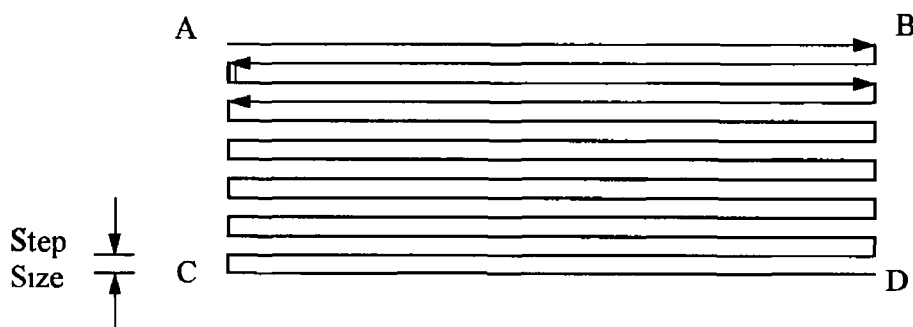


Fig 33 Plotted AutoCAD drawing

A sampling rate (S) and plotter speed (P) have now to be selected. A nominal plotter speed of 14mm/sec was selected. A sampling rate of 28Hz was then selected after the plotter speed had been determined. Using this sampling rate ensures that a data point was taken for every 0.5mm scanned. The main reason for choosing these values was

to ensure that the smallest defect we are looking for is detectable. The entire length of the scan (L) is calculated as $= 79 \times 16 + 15 \times 5 = 1339\text{mm}$. Using the formulas derived in chapter three and knowing the above values it is possible to calculate the total time it takes for the scan (T) and the total number of measurements (V) to be taken. In this case they were calculated to be 95.64secs and 2678 respectively. An important point to note is the healthy balance which must exist between S, P and L. For instance, V and S have limits of 8000 and 1000Hz respectively. Also the maximum speed capability is 420 mm/sec. Due to these limitations, and in order to reduce scan time, the optimum balance of the parameters was restricted.

In summary the set scanning parameters for this test were

Plotter speed (P) = 14mm/sec

Sampling rate (S) = 28 Hz

Length of scan (L) = 1339mm

Total scanning time (T) = 95.64secs

Number of values to be measured (V) = 2678

The only other parameter which had to be set before starting the measurement process was the trigger condition. The function of the trigger condition was to start the measurement process at a certain chosen point. For these experiments the option 'trigger from infinity' was used. This ensured that the measurement process commenced only when the sensor came within the measuring range. This of course coincided with the edge of the sample plate.

4.3.2 - Representation of output signal

When the above conditions had been selected, the measurements were started. The output from the sensor was in the form of depth measurements, obtained using the triangulation method (as described in section 3.3.1.1). As set previously the number of values to be measured was 2678, therefore an output of 2678 distinct Z coordinates was obtained. A full list of the output received for this experiment is

shown in Appendix D The readings commence at point A1 and continue down to A47 Then the next step is B1 to B47 This method is consistent until the final reading is reached which is located at BK15

One method of representing all of the recorded information is in the form of a 2D graph This helps give a clearer picture as to the meaning of all the output information Fig 34 below is a graph of all the measured data for the aluminium test

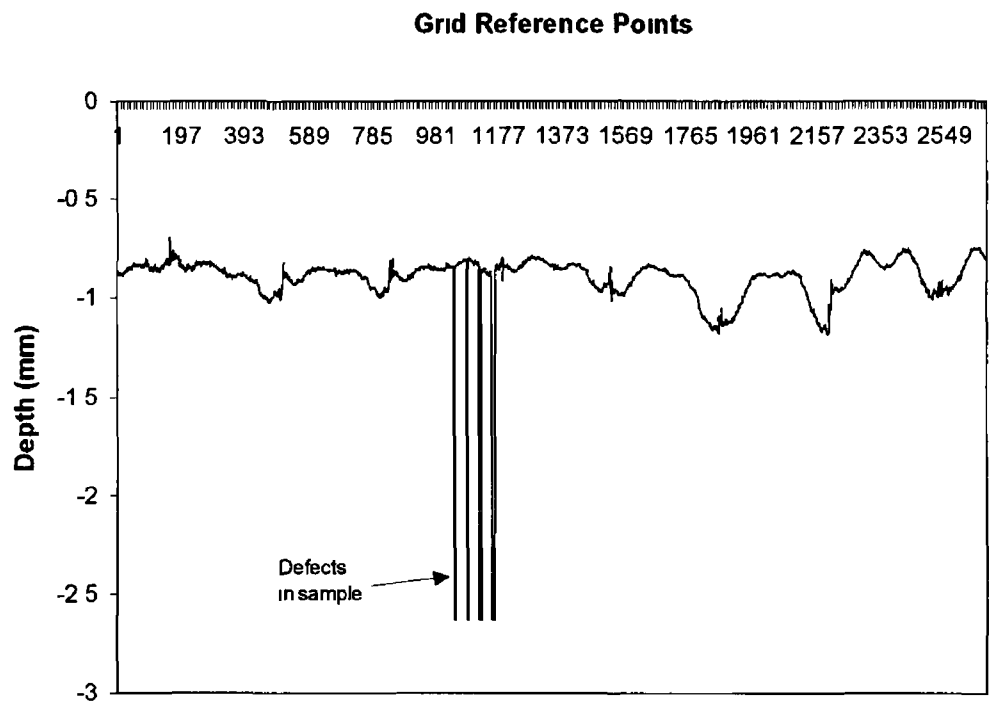


Fig 34 2D Graph of Aluminium test results

The first points to note about the graph (Fig 34) are the X and Y axes The Y-axis consists of depth measurements in mm The X-axis consists of grid reference points Therefore each reference point indicates a particular set of coordinates on the sample plate For example the data point 198 might represent a point (64,5) on the sample plate Each grid reference point on the graph is taken from Appendix D Given the scanning parameters, the values 1 to 158 constitute the first scan line from coordinates (0,0) to (79,0) and that the next 10 values are from (79,0) to (79,5) The relationship between the grid reference points and the plate coordinates can be

calculated from the scanning parameters An example of this system is shown in Table 2

Table 2 Relationship between output and coordinate system

Plate coordinates	Grid reference points	Location in App D
(0,0) (79,0)	1 158	A1 D17
(79,0) (79,5)	158 168	D17 D27
(79,5) (0,5)	168 326	D27 G44
(0,5) (0,10)	326 336	G44 H7
(0,10) (79,10)	336 494	H7 K24
(79,10) (79,15)	494 504	K24 K34
(79,15) (0,15)	504 662	K34 O4
(0,15) (0,20)	662 672	O4 O14
(0,20) (79,20)	672 830	O14 R31
(79,20) (79,25)	830 840	R31 R41
(79,25) (0,25)	840 998	R41 V11
(0,25) (0,30)	998 1008	V11 V21
(0,30) (79,30)	1008 1166	V21 Y38

The most important point to observe from the graph (Fig 34) is the four large peaks located approximately in the centre of the graph These correspond to the location of the four holes in the aluminium plate A sample of the data which represents the smallest defect is highlighted in Fig 35

	S	T	U	V	W	X	Y	Z	AA
1	-0 8806	-0 9004	-0 8475	-0 8603	-0 8453	-0 8109	-0 8526	-0 8406	-0 8654
2	-0 8882	-0 9025	-0 8507	-0 8582	-0 8429	-0 8084	-0 8482	-0 829	-0 8759
3	-0 8041	-0 8968	-0 848	-0 86	-2 6315	-0 8008	-0 8502	-0 8401	-0 873
4	-0 8592	-0 8898	-0 8417	-0 8564	-2 6315	-0 7991	-0 8502	-0 8431	-0 8691
5	-0 8629	-0 8981	-0 84	-0 8568	-2 6315	-0 8068	-0 8504	-0 8242	-0 8702
6	-0 8678	-0 8938	-0 84	-0 8568	-0 8561	-0 8059	-0 8565	-0 8244	-0 8706

Fig 35 Extract of results table in Appendix D displaying depth values in mm, with the values for the smallest defect highlighted

The height of these peaks in the graph corresponds to the depth of the holes. The holes in the plate were approximately 2.5 mm in depth. If the surface of a plate was giving a negative reading of -0.5 and the hole has a measured depth of 2.5 mm from the surface, then theoretically the bottom of the hole should give a reading of 3.0. However, the measuring limit of the sensor is -2.6, so the reading that shows up for the bottom of the hole would be the sensor's bottom limit of -2.6.

The diameter of each of the holes can be calculated from the number of data points recorded at these coordinates when compared with the speed of the scan and the sampling rate. For example, with the plotter travelling at a speed of 14 mm/sec and a sensor sampling rate of 28 Hz, this means each recorded value from the sensor is 0.5 mm apart. So if the sensor measures 12 values for the spike, this indicates a hole diameter of 6 mm.

As an indication of this fact, we observe the data points W3 to W5 (Fig 3.5). These three maximum values correspond to the smallest hole of approx. 2 mm in diameter. The fact that there are three values instead of four may seem to indicate that the sensor miscalculated the hole diameter as 1.5 mm. There are two main reasons for this error. There may be a margin of error associated with the process of drilling the holes in the plate. The other reason relates to the speed and sampling rate. There can be no guarantee that the first value W3 corresponds exactly to the edge of the hole. What is more likely is that it corresponds to a point 0.2-0.3 mm inside the edge of the hole. Therefore, if the readings are occurring every 0.5 mm, then three readings later it should have passed by the other side of the defect. So, it is logical to assume a margin of error of 1 value as to the actual size of the defect. In this case, adding one on to the three readings already recorded gives a hole diameter of $4 \times 0.5 \text{ mm} = 2 \text{ mm}$ and this indeed corresponds to the actual diameter of the hole.

The location and number of values of the other three defects are

- 1 W41 → W46 6 values
- 2 X34 → X40 7 values (+1 for error)

3 Y27 → Y35 9 values (+1 for error)

Using the method discussed above for calculating the hole diameter and allowing for the errors also discussed, the sensor gives hole diameters of 3,4,5mm which corresponds to the actual diameter of the holes

4 3 3 - Coordinate system

An important point to notice is that the grid reference point gives the exact location of these defects The actual location of these defects is given below in Fig 36

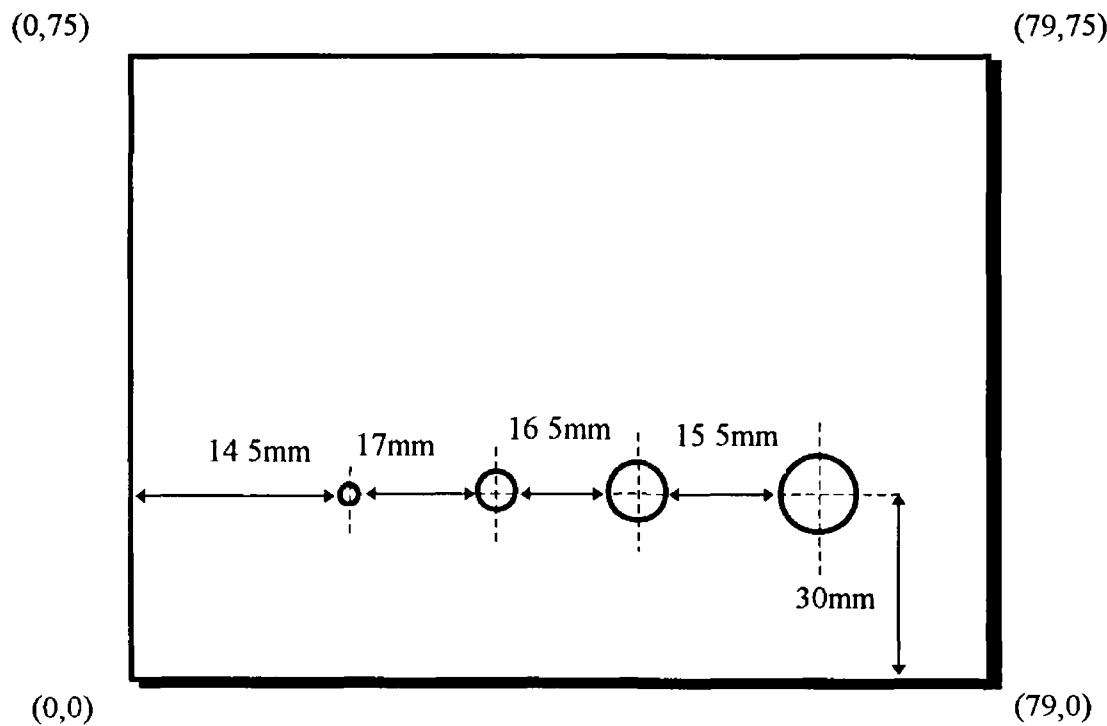


Fig 36 Actual coordinates/dimensions of sample plate

From the sensor output signal, the coordinates/dimensions were calculated using a combination of the data from Appendix D and Table 6 Calculating the coordinates using this method it was found that they corresponds almost exactly to their real coordinates (Fig 37) An error of +0.5mm that occurred for the measurements

between the holes was due to the sampling rate. Another possibility for error could be due to the movement of the plotter which was smooth.

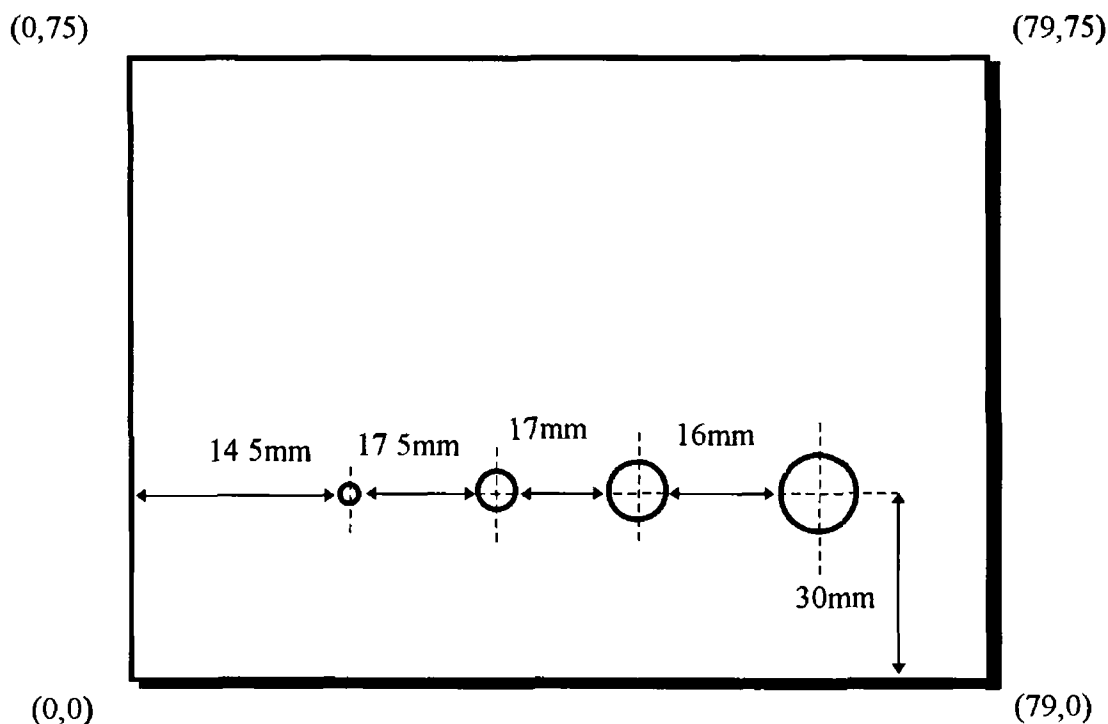


Fig 37 Coordinates/dimensions of sample plate calculated by the sensor

4.3.4 - Experimental errors

It has been explained in section 4.3.2 how the graph of the aluminium results (Fig 34) displays information about the sample plate. Detail has been given of the significance of the peaks in the graph shown in Fig 34 and how these peaks may be used to obtain an overall picture of the sample plate. However, no explanation has yet been given as to why the rest of the graph is not perfectly smooth. The first and most obvious reason relates to the plate itself. No matter how level the surface of the plate might appear to the eye, it is not a perfectly smooth surface. Therefore, a certain amount of variation in the output is to be expected, especially when such a small scale is used.

Another error is caused by the way the plate is mounted. Due to the fact that the plate is only screwed to the pen carriage on one side and the selfweight of the plate, a slight incline can arise, thus making the plate lopsided. The significance of this incline can be seen in Fig 38 and Fig 39. In order to assess how much of an incline there was, the first scan line (points 1-158) and the second scan line (points 168-326) were plotted respectively. From Fig 38 it can be seen that the values start from -0.875mm and move gradually upwards until they peak at roughly -0.8mm. Conversely in Fig 39 the values range from -0.8mm down to -0.875mm.

The similarity of this variance indicated a slope of $\pm 0.075\text{mm}$ for every 79mm depending on which direction being travelled in. Or in other words a gradient of 0.05° .

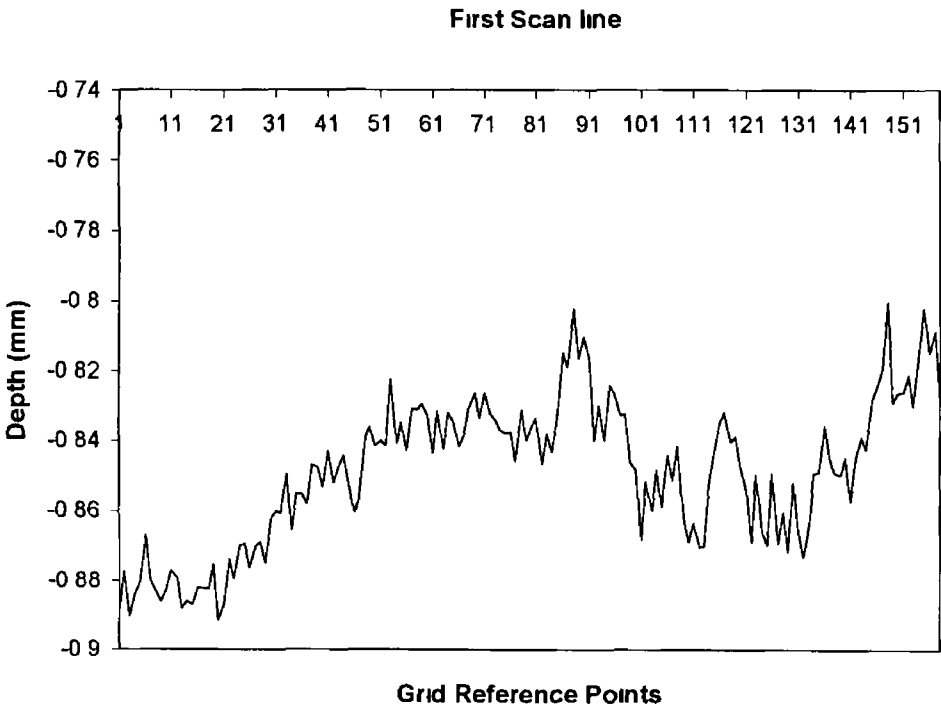


Fig 38 Graph of results for first scan line

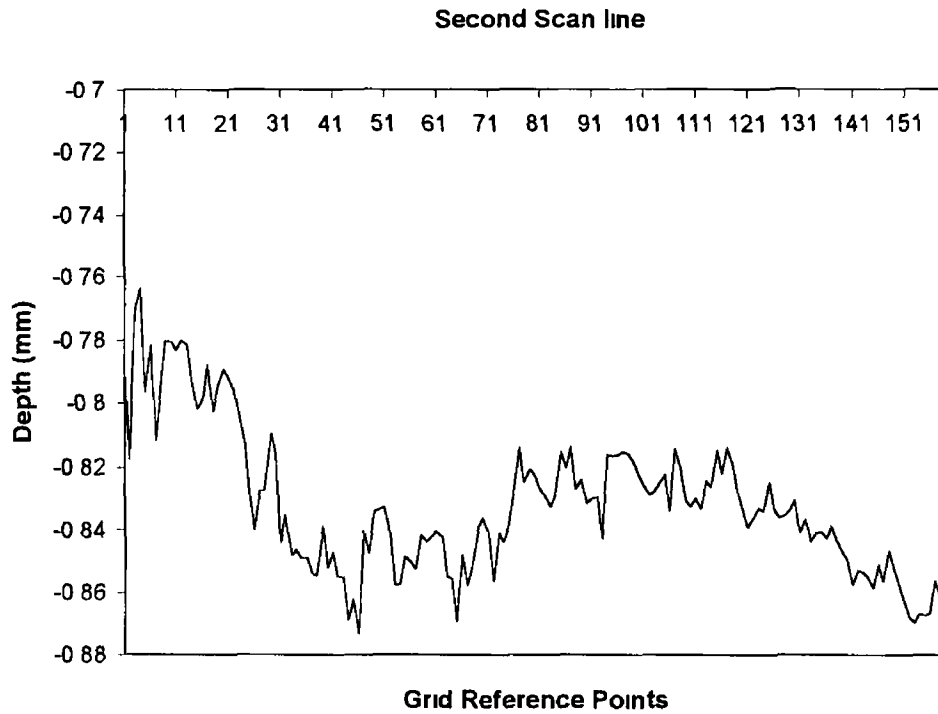


Fig 39 Graph of results for second scan line

Another possibility for errors in the graph is the movement of the plotter itself. This movement causes vibrations in the plate which affect the readings. This effect is more pronounced when the plotter is changing direction.

In summary there are three main experimental errors inherent in the system, these are,

- 1 Uneven plate surface
- 2 Gradient of plate
- 3 Plotter vibrations

4.3.5 - 3D view of surface

Finally, having obtained X, Y and Z(depth) coordinates for the sample plate it is now possible to plot a 3D graphical image of the sample plate (Fig 40). This graph was plotted using the EXCEL package. A macro program was written in EXCEL using

Visual Basic in order to facilitate the manipulating of all the data into an appropriate grid system Details of this macro program can be seen in Appendix C

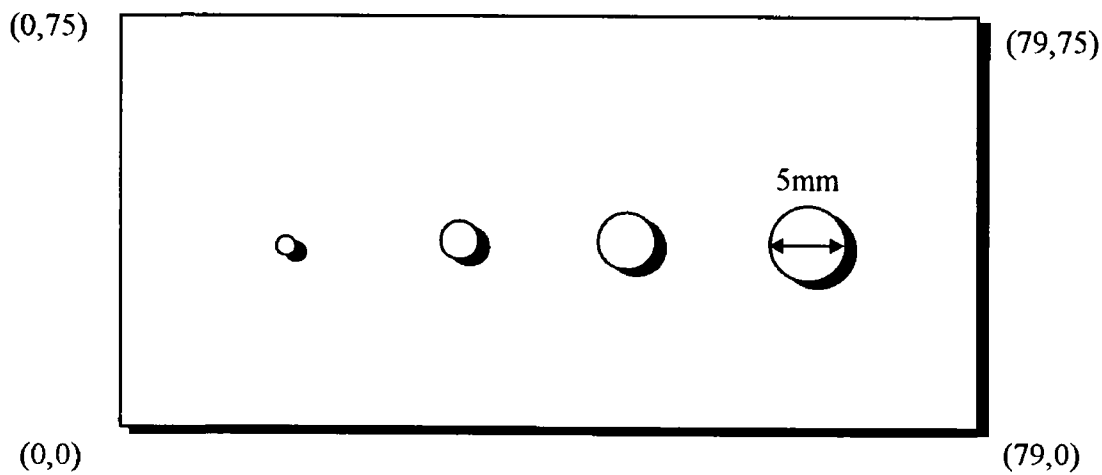
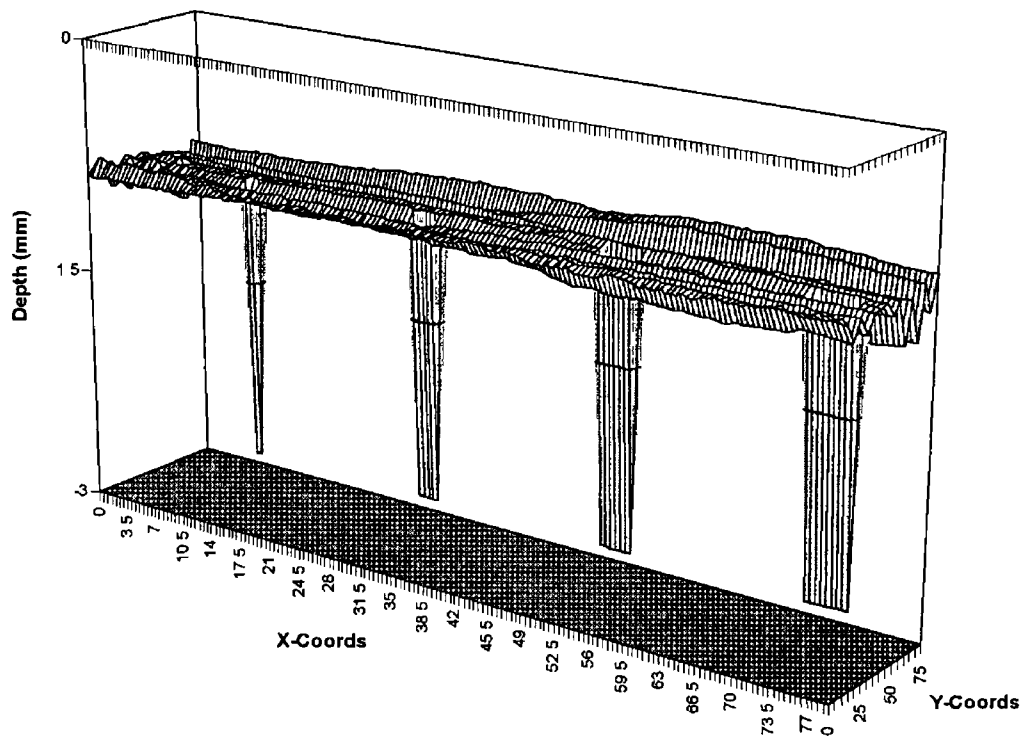


Fig 40 3D Graph of aluminium plate compared to actual sample plate

However, this graph is not to scale as none of the values measured during each stepping motion are plotted. These were omitted in order to speed up the graphing process and because they were not critical to the overall picture of the 3D graph.

For the other materials tested it is not necessary to explain once again how certain values and parameters were calculated. It is enough to say that any method of calculation or experimental technique used in the aluminium experiments were also used in the other experiments.

4 4 - Stainless Steel digital tests

The surface of the material contained The first set of these defects consisted of 7 holes with diameters ranging from 7mm to 2mm in decreasing steps of 1mm all of which had a depth of 2.6mm The second set of defects consisted of 5 holes with diameters ranging from 8,6,6,5 and 3mm all of which had a depth of 0.6mm The rest of the materials tested after stainless steel were given the same type of defect at the same location in order to aid the examination of the effect of different materials The scanning parameters were the same as those used for the aluminium experiments These parameters were kept constant for all the digital experiments

After several tests all of which proved consistent with one another the output was once again first plotted in the form of a 2D graph (Fig 41)

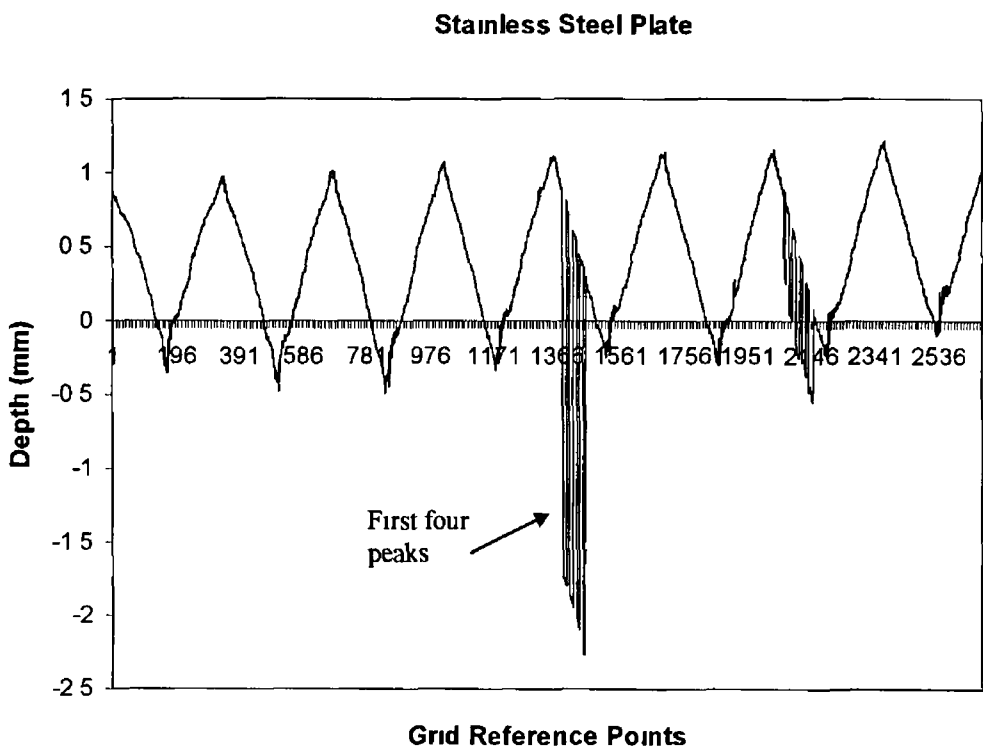


Fig 41 2D Graph of Stainless Steel test results

As can be seen from the graph (Fig 41), the first set of defects show up around the centre of the scan It may not be very clear from the graph but there are four distinct peaks as opposed to the six defects which are actually in the sample The four defects

which appear are the four largest defects Fig 42 gives a view of the data points 1370 → 1460 in order to get a clearer view of these peaks The sensor determines their depth and diameter using the same method as for the aluminium results The reason that the other two defects do not appear in the graph is not because the sensor was unable to measure them It is due to the scanning pattern determined at the start of the scan In the beginning it was determined to have a scan step size of 5mm So the defects of 2 and 3mm unfortunately happen to have fallen in between scan lines In order to ensure this does not happen it would be necessary to change the step size to the smallest defect we need to find However, there are limitations to changing the step size as it effects other scanning parameters (section 4 3 1)

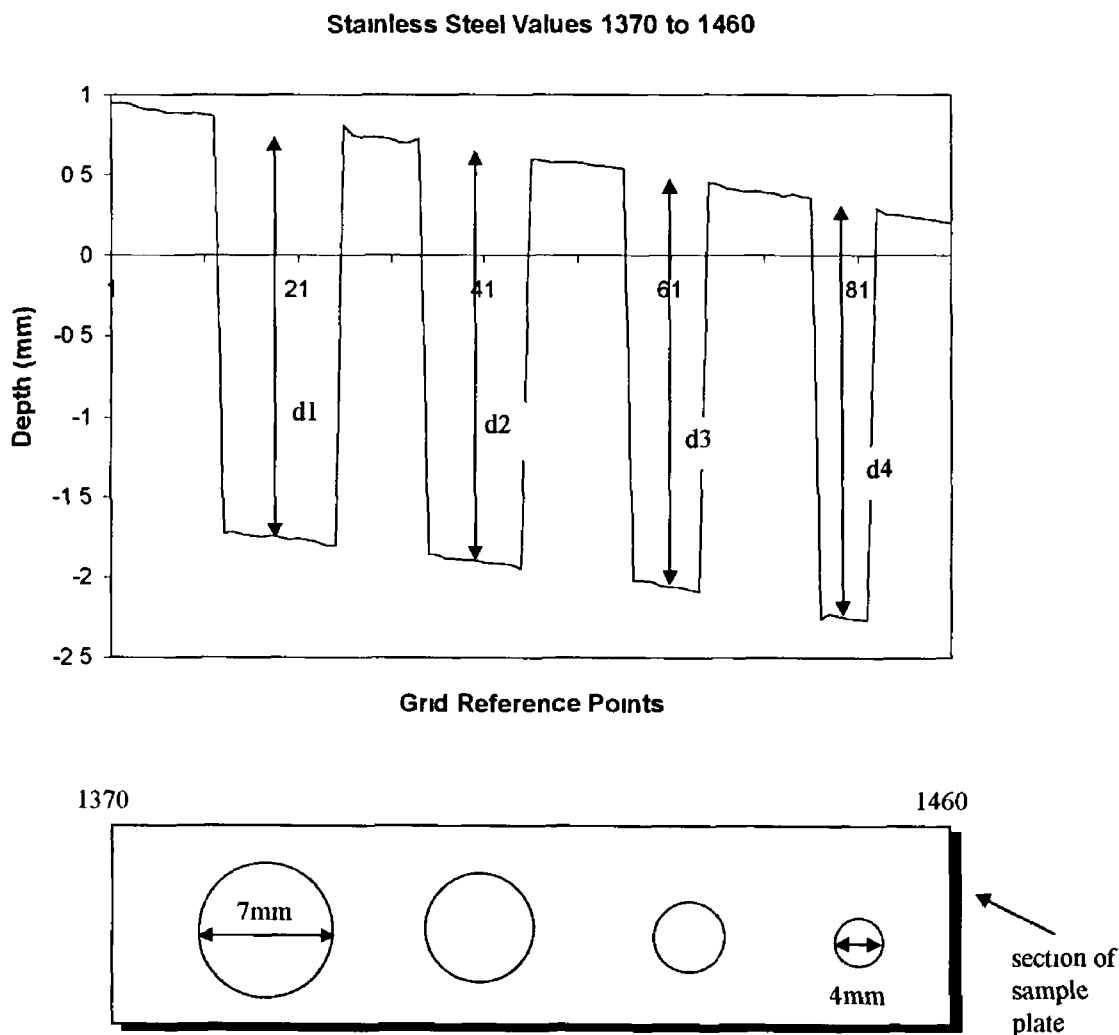


Fig 42 Graph of Stainless Steel results of points 1370 to 1460 and their corresponding plate coordinates

It appears from Fig 42 that the depth increases as the hole diameter reduces. However, on closer examination the depth actually remains reasonably constant (d1-d4) but the self-weight of the plate (section 4.3.4) causes an incline which makes the depth harder to determine clearly.

The second set of peaks indicate the second set of defects. In this set there are five peaks which indicate that all five defects have shown up (Fig 43).

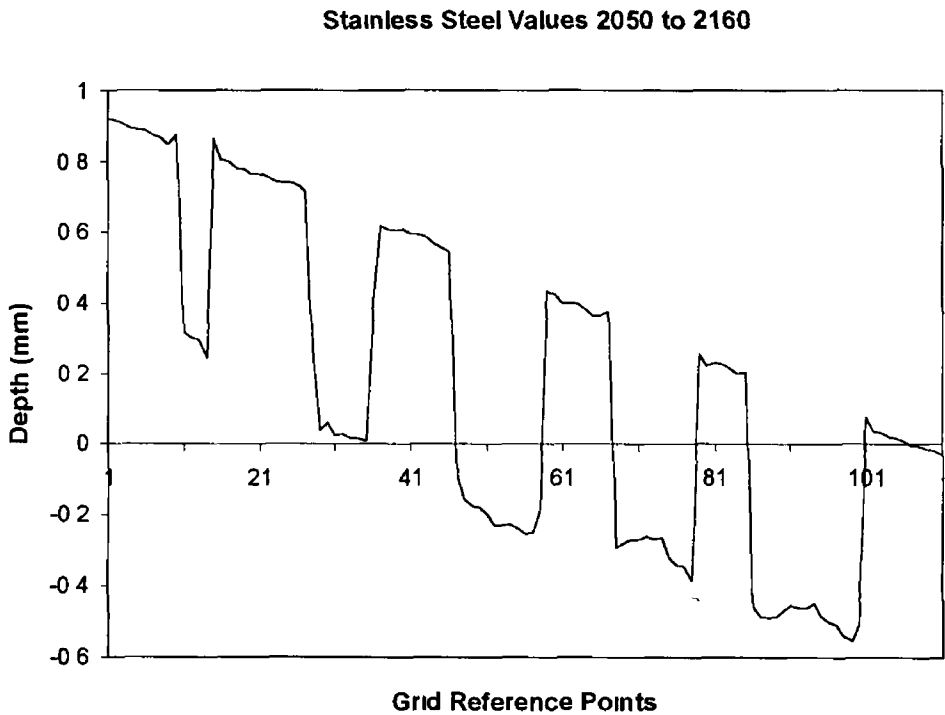


Fig 43 Graph of Stainless Steel results of points 2050 to 2160

A summary of the actual characteristics of the defects of the stainless steel plate as opposed to those registered on the sensor is given in Table 7. The actual defect width/depth measurements were made with a verniers and the measured indicates that taken by the sensor.

Table 7 Calculated characteristics of the Stainless Steel plate

Scan line No	Actual defect width(mm)	Measured defect width	Actual defect depth(mm)	Measured defect depth
9	7	6.5	2.6	2.6011
9	6	5.5	2.6	2.5881
9	5	4	2.6	2.5663
9	4	3	2.6	2.6134
9	3	-	2.6	-
9	2	-	2.6	-
13	3	2	0.6	0.5601
13	5	4.5	0.6	0.5726
13	6	6	0.6	0.6225
13	6	5.5	0.6	0.5972
13	8	7.5	0.6	0.5842

From Table 7 it can be seen that the sensor measures very accurately. However, there are some discrepancies between the vernier and the sensor values which should be explained. Some reasons have already been given as to why the sensor fails to measure the smaller defects. It should also be noted that there is no way of ensuring that the sensor passes directly over the widest part of any defect. Added to the reason already suggested in the aluminium results as to too large a step size, this gives a margin of error associated with the defect width. Finally as regards the depth of the defect, the sensor is a much more sensitive measuring instrument than the verniers and therefore measures the depth more accurately.

Another main point to note about the graph (Fig 41) is its apparent sinusoidal nature. The reason for this is that it was mounted on a slope. The effect of this slope is more pronounced than that in the aluminium results. This is because the plate was mounted on top of the aluminium plate. Therefore, the additional weight results in a more exaggerated slope. In fact the slope was calculated as 1.08° . The good part about this slope is that it makes it much easier to identify each line of the scan.

4.5 - Brass digital tests

The surface of the brass material contained two basic defects. The first set of these defects consisted of 7 holes with diameters ranging from 7mm to 2mm in decreasing steps of 1mm all of which had a depth of 2.6mm. The second set of defects consisted of 5 defects with diameters ranging from 8,6,5,4 and 3mm all of which had a depth of 0.6mm.

The experimental settings/parameters were consistent with all of the other digital experiments. A plot of the typical results obtained can be seen in Fig 44.

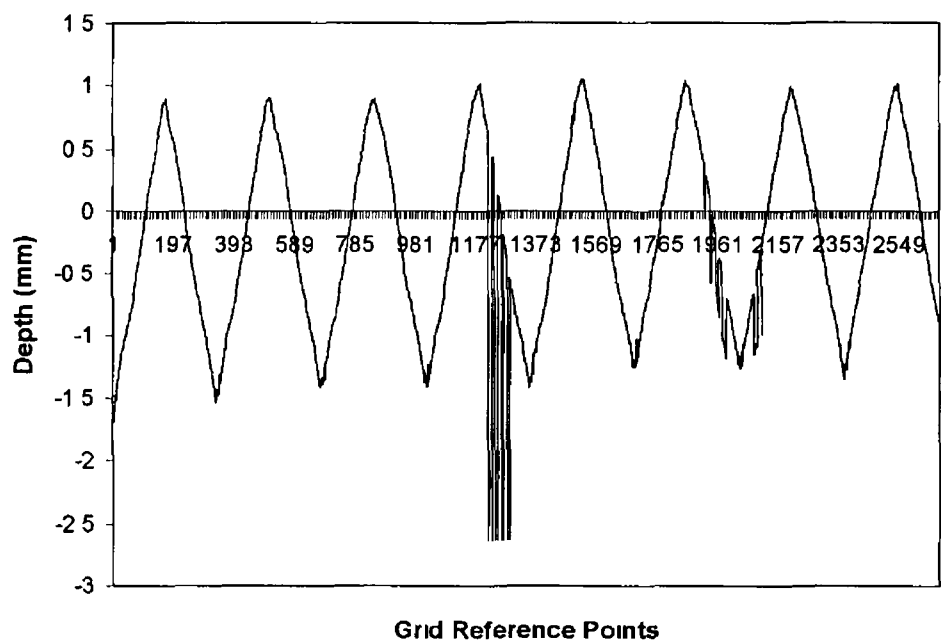


Fig 44 2D Graph of Brass test results

As before two distinct set of peaks stand out in the middle of the graph. Graphs of these two important sections can be seen in Fig 45 and Fig 46. There is an important difference between these results compared to those obtained with stainless steel. The first observation is that the defects have shown up in different scan lines. The reason

for this is that the initial positioning of the brass plate was slightly off to that of the stainless steel plate. For this reason, the sensor commenced measuring during its second scan line and so reached the defects at a different position in the scan. This slight change in positioning also affected the position at which the sensor crossed the defects. In fact it is likely that the scan line failed to coincide with the centres of the defects. Confirmation of this fact can be seen in Fig 46. On the bigger two defects of widths 8 and 6mm, they have shown up on the next scan line. In other words these defects fall on two different scan lines.

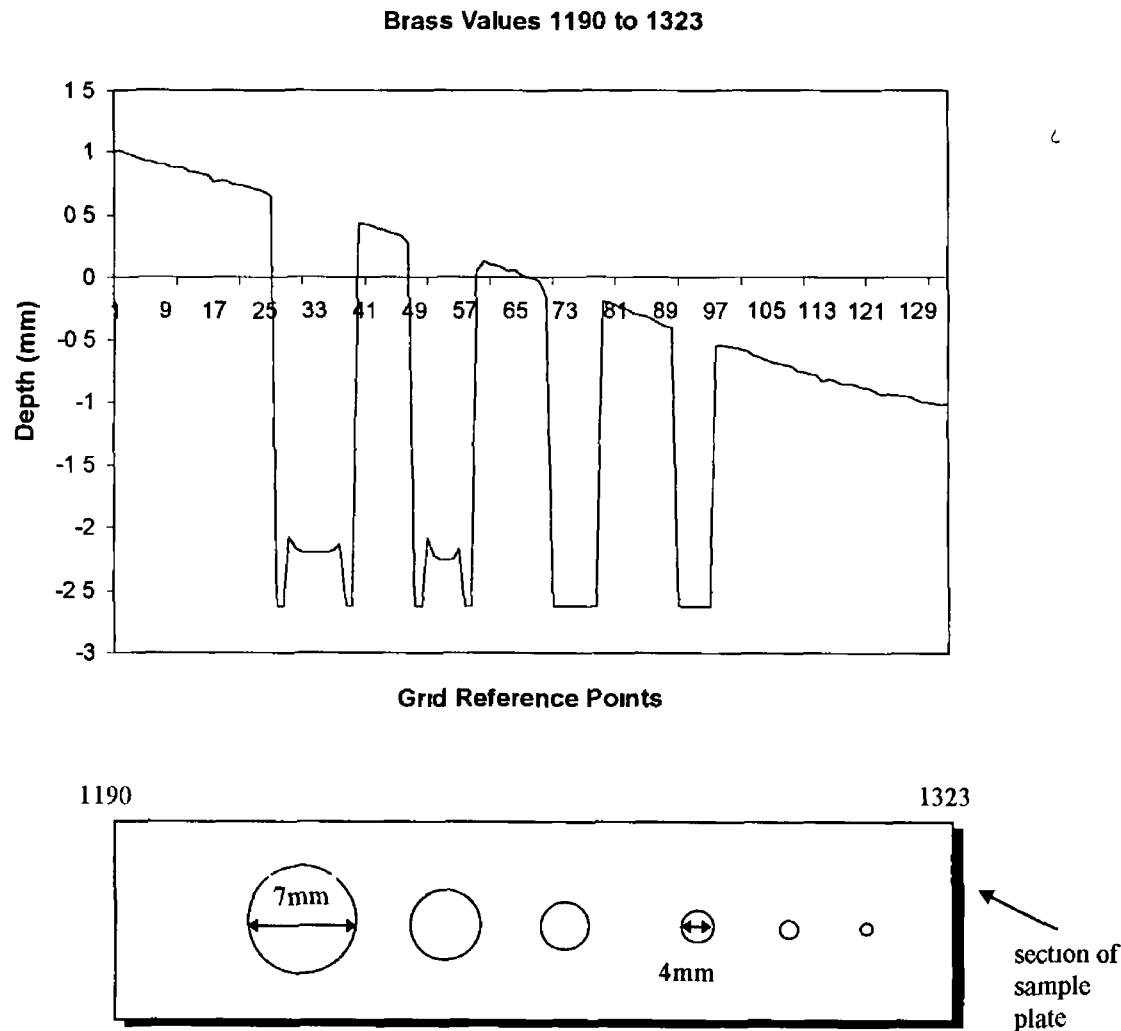


Fig 45 Graph of Brass results of points 1190 to 1323 and their corresponding plate coordinates

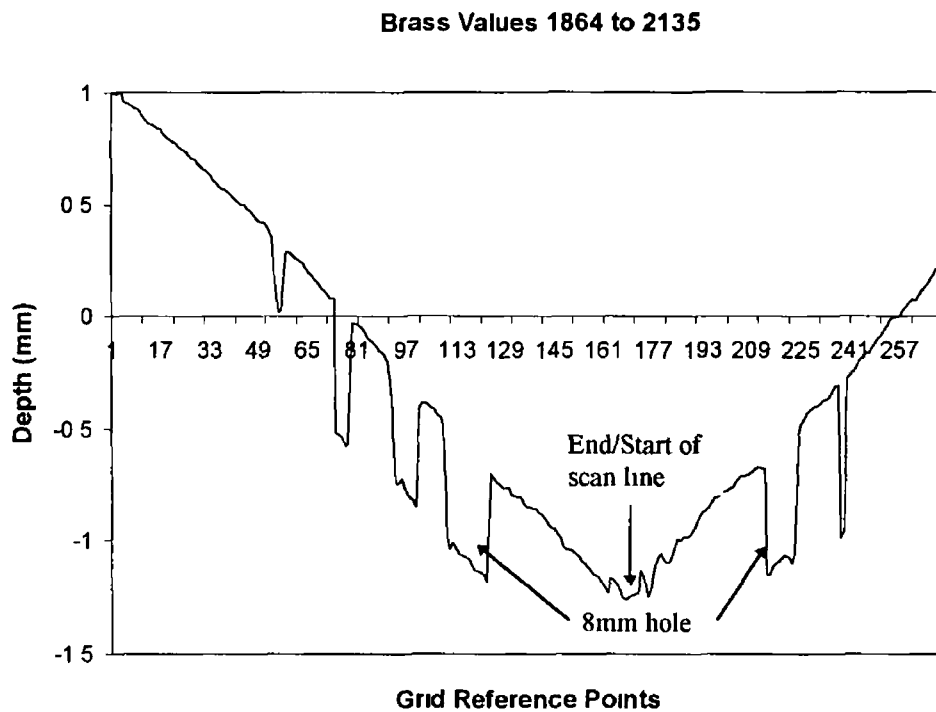


Fig 46 Graph of brass results of points 1864 to 2135

Table 8 below gives a summary of the characteristics recorded for the brass plate

Table 8. Calculated characteristics of the Brass plate

Scan line No	Actual defect width(mm)	Measured defect width	Actual defect depth(mm)	Measured defect depth
8	7	6 5	2 6	2 7225
8	6	5	2 6	2 5264
8	5	4	2 6	>2 437
8	4	3	2 6	>2 2225
8	3	-	2 6	-
8	2	-	2 6	-
12	3	-	0 6	-
12	4	2	0 6	0 3167
12	5	2 5	0 6	0 5978
12	6	3 5	0 6	0 5256
12	8	7	0 6	0 5566

The initial alignment of the plate is one of the main reasons why the measured values do not correspond exactly to the actual values. It should be noticed that some of the measured depths could not be calculated as they extended beyond the maximum measuring limit of the sensor (section 4.3.2). Therefore all we can say with certainty about these depths is that they are greater than a certain depth value. Other errors discussed earlier for the stainless steel and aluminum results also occurred with the brass test plate. The average gradient of the plate was calculated to be 1.81° . This gradient is directly related to the self-weight of the plate and also a cause of error.

4.6 - Copper digital tests

The surface of the copper material contained two basic defects. The first set of these defects consisted of 7 holes with diameters ranging from 7mm to 2mm in decreasing steps of 1mm all of which had a depth of 3.5mm. The second set of defects consisted of 5 defects with diameters ranging from 8, 6, 5, 4 and 3mm all of which had a depth of 0.6mm. These defects were similar in both position and size to those of the brass plate, the only difference being the depth of the holes.

The experimental settings/parameters were consistent with all of the other digital experiments. A plot of the typical results obtained can be seen in Fig 47.

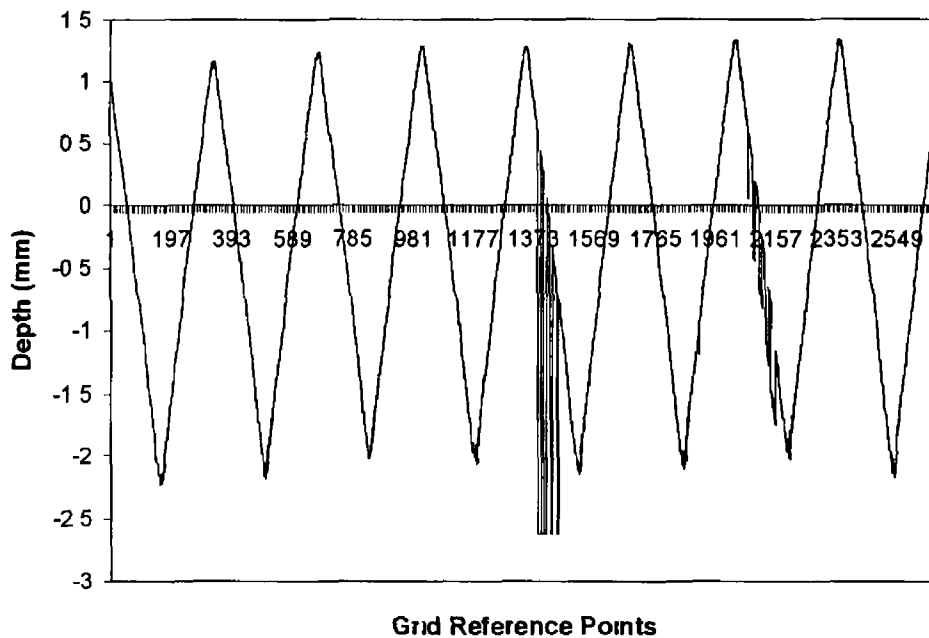


Fig 47 2D Graph of copper test results

The first point to note about Fig 47 is that it bears a strong resemblance to the stainless steel results presented in Fig 41. The position on the graph of where the defects appear is almost identical to that recorded for the stainless steel plate. This is due to an almost identical positioning of these plates during the set up procedure. A closer inspection of the defect areas can be seen in Fig 48 and Fig 49. It can be seen that once again the smallest two defects in the first set of holes has again been missed. This is mainly due to the step size selected. However all of the second set of defects have shown up. Again these two graphs show a strong resemblance to the same analysis graphs in stainless steel. This resemblance would indicate a consistency on the part of the sensor in the measuring of metal surfaces.

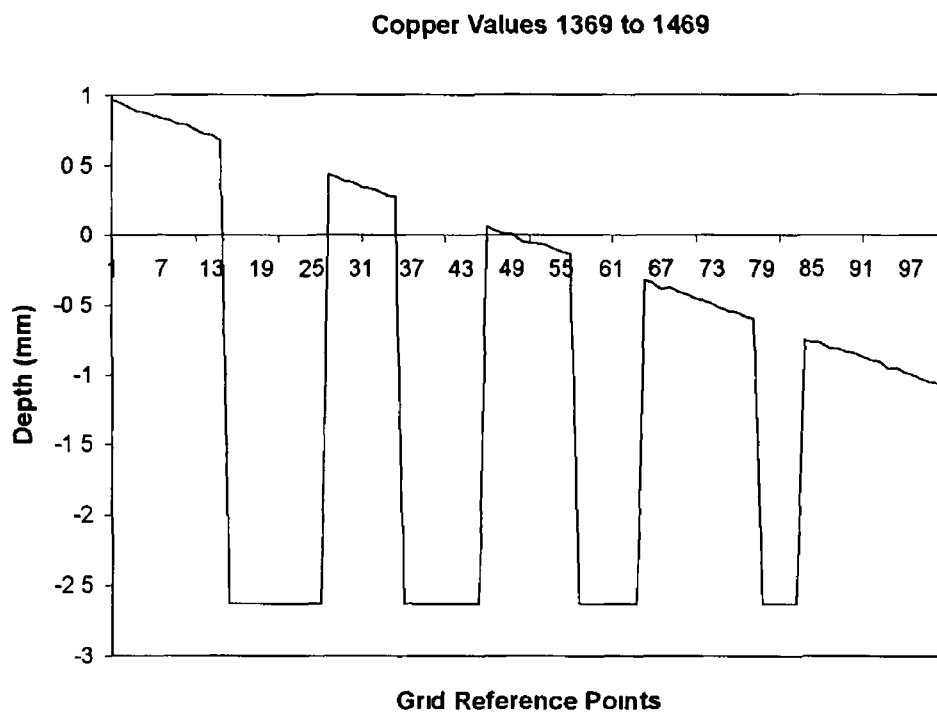


Fig 48 Graph of Copper results of points 1369 to 1469

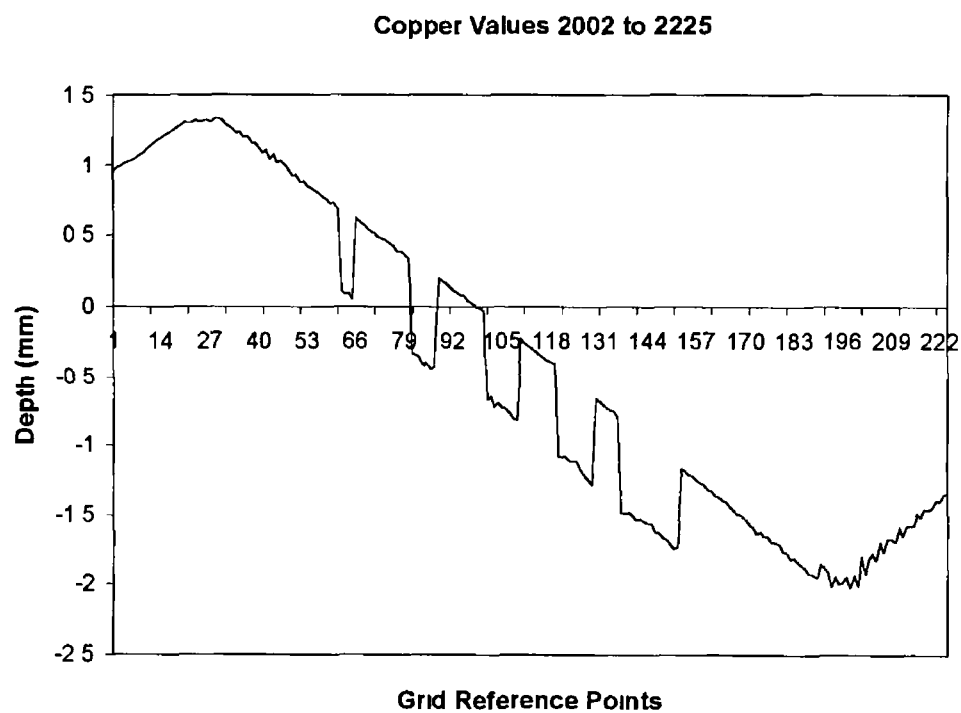


Fig 49 Graph of Copper results of points 2002 to 2225

Table 9 below gives a summary of the characteristics recorded for the copper plate

Table 9 Calculated characteristics of the Copper plate

Scan line No	Actual defect width(mm)	Measured defect width	Actual defect depth(mm)	Measured defect depth
9	7	6	3.5	>3.0596
9	6	5	3.5	>2.6852
9	5	4	3.5	>2.4913
9	4	2.5	3.5	>2.0293
9	3	-	3.5	-
9	2	-	3.5	-
13	3	2	0.6	0.5773
13	4	3.5	0.6	0.6227
13	5	4.5	0.6	0.6326
13	6	5	0.6	0.6212
13	8	8	0.6	0.6758

The calculated characteristics are reasonably consistent with those that have appeared for all the other materials. As with some of the brass results, for some of the defects the full depth cannot be calculated as the sensor reaches its maximum measuring limit. Possible error influences in the readings are consistent to those stated for the other materials.

The average gradient of the plate was calculated to be 2.5° . The reason for this slope being higher than the other materials is mainly due to the fact that copper is heavier than the other materials.

4.7 - polycarbonate digital tests

The surface of the polycarbonate material contained two basic defects. The first set consisted of 7 holes with diameters ranging from 7mm to 2mm in decreasing steps of

1mm all of which had a depth of 5mm The second set of 5 defects had diameters ranging from 8,6,5,4 and 3mm some of which had a depth of 0.6mm and some with a depth of 0.7mm Apart from their respective depths these defects were identical in both position and width to that of the brass and copper plate

The experimental settings/parameters were consistent with all of the other digital experiments A plot of the typical results obtained can be seen in Fig 50

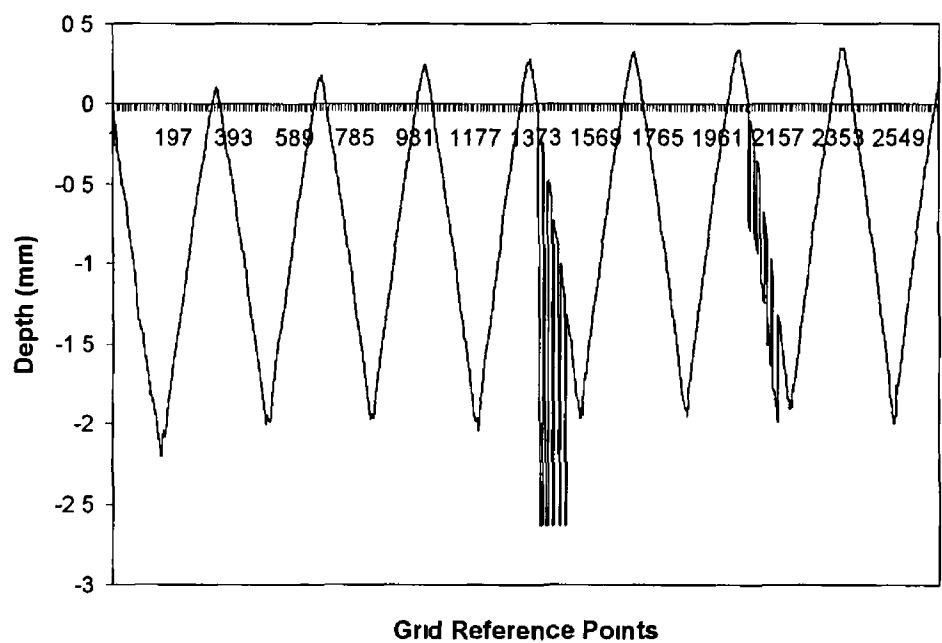


Fig 50 2D Graph of Polycarbonate test results

The first point to note about Fig 50 is that it bears a strong resemblance to the stainless steel and copper results The position on the graph at which the defects appear is almost identical to those of both the stainless steel and copper plates The similar set up procedure used for each material would account for this A closer inspection of the defect areas can be seen in Fig 51 and Fig 52 However, the one major difference in these test compared to all the others is that one of the smaller defects has shown up for the first time The most probable explanation is that the

sample plate was almost ideally aligned for the sensor to scan over the centre of the defects

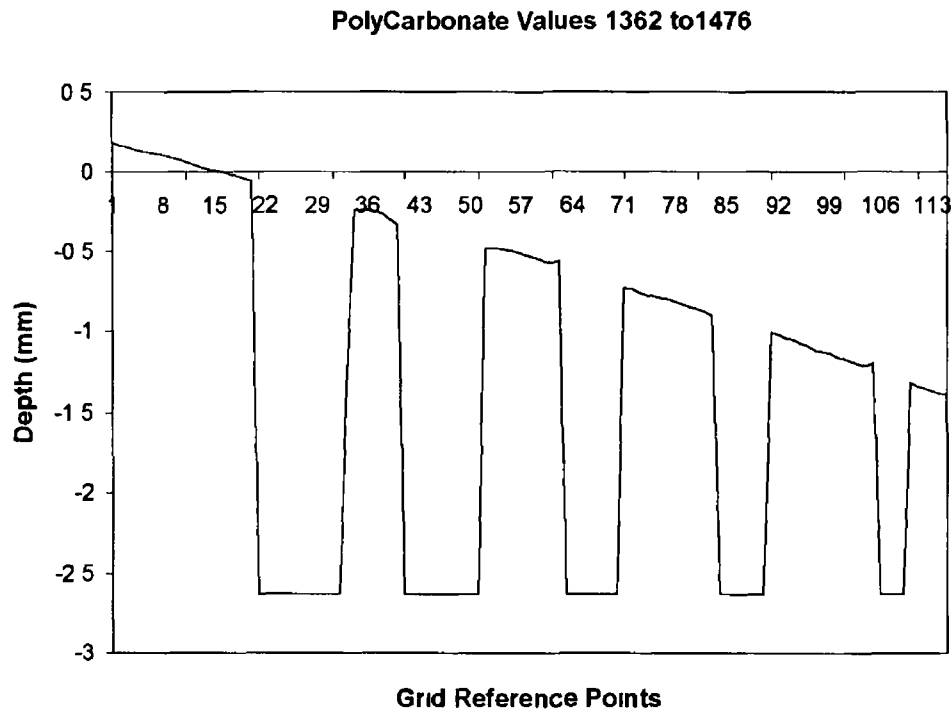


Fig 51 Graph of polycarbonate results of points 1362 to 1476

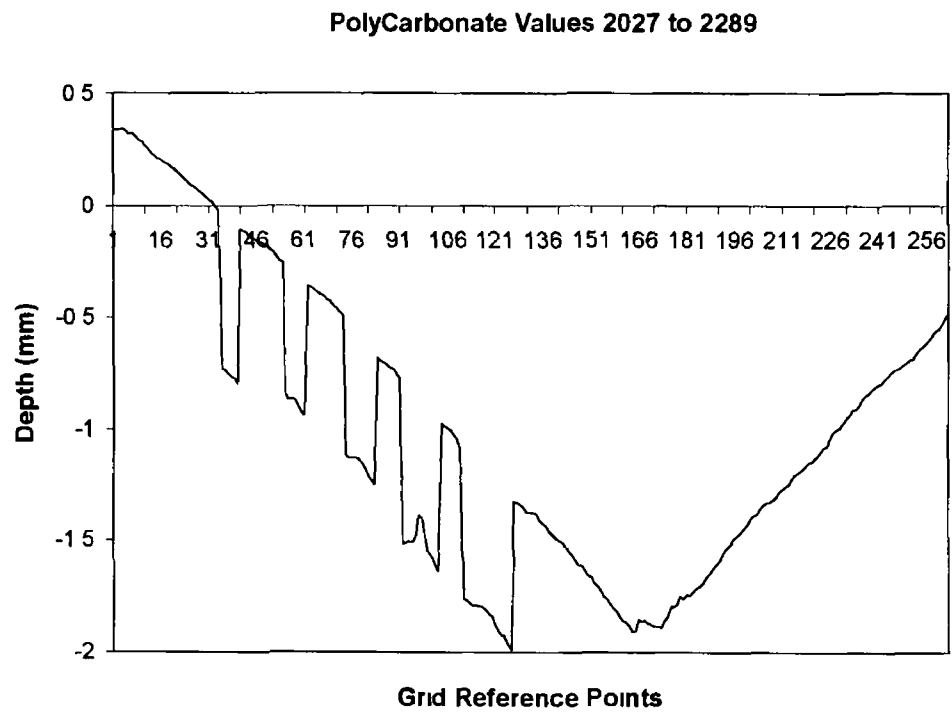


Fig 52 Graph of polycarbonate results of points 2027 to 2289

Table 10 below gives a summary of the characteristics recorded for the polycarbonate plate

Table 10 Calculated characteristics of the Polycarbonate plate

Scan line No	Actual defect width(mm)	Measured defect width	Actual defect depth(mm)	Measured defect depth
9	7	6.5	5	>2.5554
9	6	5.5	5	>2.2830
9	5	4.5	5	>2.0582
9	4	3.5	5	>1.7168
9	3	2	5	>0.6565
9	2	-	5	-
13	3	3	0.7	0.6912
13	4	3.5	0.6	0.5849
13	5	5	0.6	0.6290
13	6	6	0.7	0.6827
13	8	8	0.7	0.6804

These set of results are the most accurate of all the tests performed in measuring the hole diameters. Firstly, the scan line must have almost coincided with the centre line of the defects. Secondly, the material itself must be strongly compatible to the sensor. It was stated about the sensor that a white surface was the most ideal measuring surface for the sensor. Since polycarbonate has a white finish it might account for the increased accuracy of the sensors measurements. The reason that the depth of the holes could not be fully measured is again because they exceed the maximum measuring limit of the sensor.

The average gradient of the plate was calculated to be 1.45° . As expected the slope would not be as prominent as the copper plate. This is of course because polycarbonate is a lighter material. However, because the sample used was much

thicker than any of the others it contributed to a certain self-weight factor ensuring a slope

4.8 - Perspex digital tests

The size and placement of the defects on the perspex plate was the exact same as those on the brass sample. All the scanning parameters were also the same as in the other tests. However, as is clearly visible from the graph (Fig 53), the test outcome was entirely different. The actual data received from the sensor contained no apparent pattern with a series of peaks and troughs located randomly through the graph. The reason for this result can be attributed to the material being scanned Perspex as we know is a transparent material and therefore there is insufficient reflection from the surface to give consistent results. This is one of the limitations of the sensor being used. However, one redeeming feature about the graph is that it shows a concentration of peaks at the same grid reference points as in the stainless steel graph. The location of the defects in the perspex plate is the same as that of the stainless steel plate. This would indicate that even with a transparent material such as perspex the sensor seems capable of reacting to surface defects.

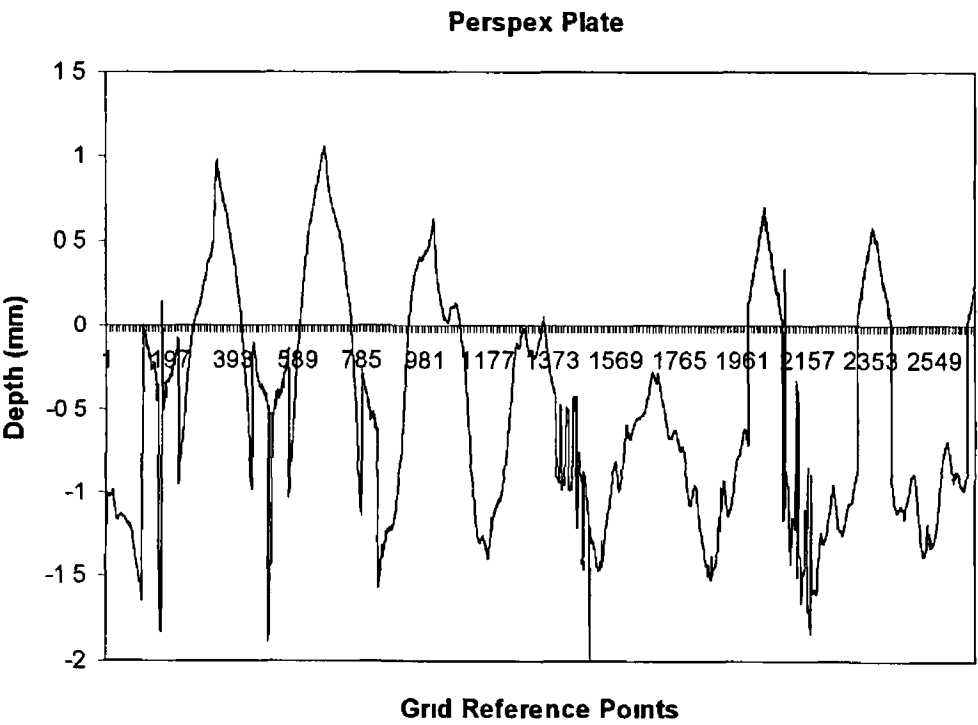


Fig 53 2D Graph of Perspex test results

5 9 - Summary of results of materials tested

Table 11 below gives a summary of all the materials tested The conclusions to be derived from these results are presented in the next chapter

Table 11 Summary of Results

Material type	No of defects in sample plate	No of defects in plate detected	Average margin of error in calculated hole diams (mm)
Aluminium	4	4	0 38
Stainless Steel	11	9	0 61
Brass	11	8	1 44
Copper	11	9	0 83
Polycarbonate	11	10	0 35
Perspex	11	0	-

CHAPTER FIVE

CHAPTER FIVE

5.- Conclusions and Recommendations for further work

5.1 - General conclusions

The objective of this project was the development of a low cost laser scanning system for the detection of large surface defects. In conclusion we need to examine both the systems hardware and software development. For the experiments carried out it was intended to assess the sensors measuring ability under certain headings. The two main headings covered were accuracy and repeatability. Other important subjects included examining the measuring limits of the system, the effect of using materials of different reflection abilities and the cause of errors in the system.

5.2 - System hardware development

Laser sensor

- The sensor has a capability for high speed data acquisition (up to 10kHz sampling frequency)
- It has a high resolution capability (spot size of laser 50 μ m)
- It is capable of outputting both an analog and a digital signal

X-Y Table

- The X-Y scanning motion was achieved by the use of a Roland DXY 1300 plotter
- It has the facility of varying scanning speed (from 30 to 420 mm/sec)
- The movement of the plotter can be programmed through either Windows applications or programs written in BASIC

5.3.- System software development

There are four main pieces of software developed for this system.

Windows software

The function of this software is to make possible taking measurements with the sensor ILD 2005 under WINDOWS. This program was designed by a German company Micro-epsilon. There are certain limitations in measuring parameters by running the package under WINDOWS.

- The maximum sampling rate under WINDOWS is 1kHz
- The minimum sampling rate is now 1Hz
- The maximum number of measurements which can be obtained is 8000

AutoCad

This was one of the methods for control of the plotter. Each drawing used had to be configured to the scanning parameters.

- It has the ability of outputting a scanning speed in steps of 1 to 42
- The drawing was easily changed to facilitate different step sizes and length of scan
- The position of the drawing could be moved to coincide with the edges of the sample plate to be scanned

Control through the command system

This is the second method for controlling the plotter through the computer. The DXY 1300 series comes with two internal command systems: DXY-GL and RD-GLI. The plotter can be used by selecting either of them. The DXY-GL and RD-GLI commands have the following characteristics.

DXY-GL Commands

- There are 22 types of command
- Each command executes completely without the need of others
- They make the writing of programs quite easy
- They are compatible with Roland DG's DXY plotter commands
- They have a certain degree of compatibility with Roland DG's CAMM-GL I command system for the CAMM-3 modelling machine and CAMM-GL II command system for the CAMM-2 engraving machine
- They can call RD-GL I commands into use

RD-GL I Commands

- There are 56 types of command
- Several commands must be combined to execute one action
- They make programming somewhat difficult
- They permit high definition
- They are compatible with Roland DG's RD-GL plotter commands

Macro visual basic program

- This program was developed in order to facilitate the drawing of a 3D graph
- It speeded up the analysis of results significantly
- It provided a consistent way of analysing each set of results

The system has proved accurate and given dependable results for the repeated tests that were carried out. Clearly improvements in the system specifications can be made with the acquisition of more accurate equipment, but this system is important in that it operates under the same principals as a more expensive rig.

5.3.- Conclusions on the experimental results

Accuracy

- For each of the materials tested a reasonable degree of accuracy was obtained. In the previous chapter each section gives a table of results on measurement accuracy. Any discrepancies in the values obtained were due to errors encountered in the system and not due to the inability of the sensor to measure small defects. The sensor proved accurate in measuring a variety of defects of varying sizes.

Repeatability

- The repeatability of measurements also proved extremely consistent. Any of the results produced were consistent with similar tests that were carried out. The only material that caused a problem was perspex. This was due to the transparent nature of the material

Experimental errors

- There are three main experimental errors in the system. The first and most obvious reason for error was the plate itself. No matter how level the surface of the plate might appear to the eye, it is not a perfectly smooth surface. Therefore, a certain amount of variation in the output results was to be expected, especially using such a small scale.
- Another possibility for errors in the graph is the movement of the plotter itself. This movement causes vibrations in the plate and this will effect the readings. The effect is more pronounced when the plotter is changing direction.

- Finally due to the fact that the plate is only screwed to the plotter pen carriage on one side, and the self-weight of the plate itself, a slight incline in the plate has been caused.

5.5.- Recommendations for further work

- 1.- the first recommendation concerns further testing of the rig using different materials. For all the experiments carried out up to this point the only materials tested have been metals and plastics. Each material has a different degree of reflection. Therefore, it is important to continue testing the system to establish fully what limitations exist as regards surfaces to be measured.
- 2.- The initial measuring parameters used in each test could be altered for a greater variety of values. Some limitations already exist as to the numbers that can be assigned to these parameters. For example, the maximum number of values that can be taken using WINDOWS is 8000. However, it is possible to change certain parameters such as step size and not exceed the maximum limit. Adjusting these parameters would assist in optimising the measurement process to ensure that no defect would be overlooked.
- 3.- Finally, the acquisition of more sophisticated equipment would help eliminate some of the errors associated with the current rig. For instance a proper X-Y table could be used instead of the current arrangement with the Roland DXY 1300 plotter. This would help eliminate errors due to plotter vibrations and the gradient of the sample plate. Another possibility would be the acquisition of a sensor with a spot size smaller than 50 μ m. This would enable the system to measure even smaller defects.

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APPENDICES

APPENDIX A1

OPERATIONAL FEATURES OF ROLAND DXY 1300 PLOTTER

Fig A1.1. gives a side view and a look at the rear panel of the plotter. Following this diagram there is a description of the operational features which are highlighted.

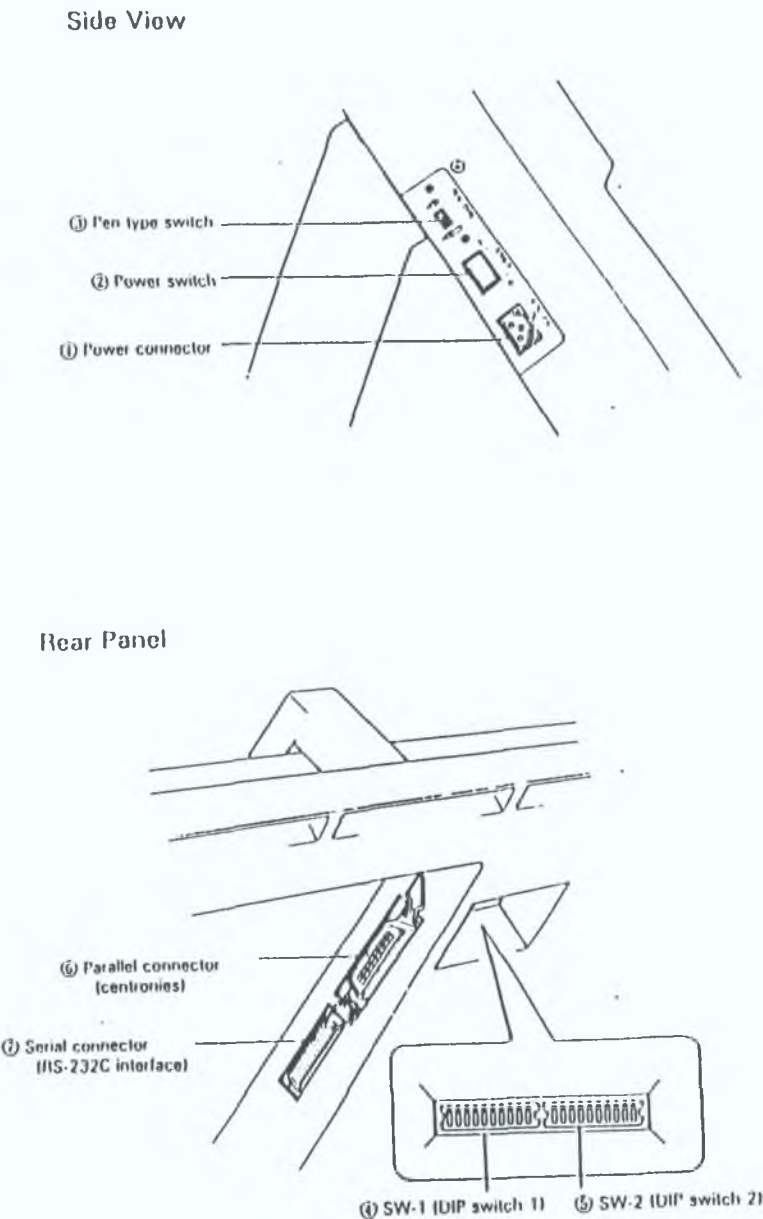


Fig A1.1. Some of the main operational functions.

1. *Power supply connector*

This is the connector for the AC adaptor

2. *Power switch*

This turns on the power. The automatic origin setting operates and then the X-Y coordinate values are displayed as (0,0).

3. *Pen type switch*

This switch is used to prevent blurring or skipping in the drawing, depending on the type of pen in use.

4. *SW-1 (DIP switch 1)*

This switch is used to select the interface (parallel or serial), set paper size and character font etc.

5. *SW-2 (DIP switch 2)*

This switch is used to set the data format and Baud rate when the serial interface is used

6./7. *I/O connector*

These connectors are used to connect the DXY-1000 series with the computer. Either the parallel or serial interface connector may be used depending on the data input/output format.

The main part of the plotter used for manual control is the operational panel. A diagram of this important panel can be seen in Fig A1.2. Again its important features will be described after the diagram.

Operation Panel

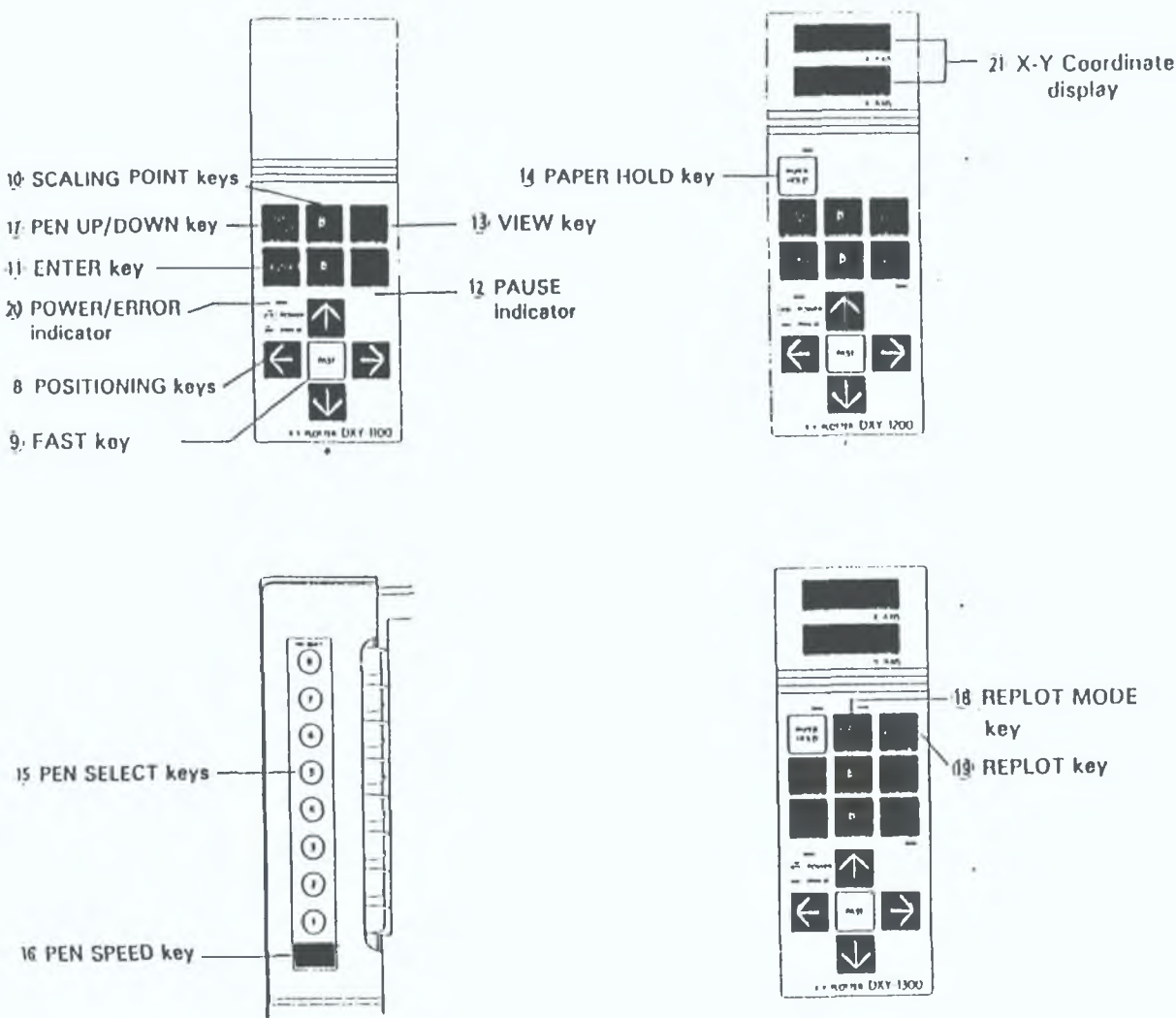


Fig A1.2. Control panel on the plotter.

8. *POSITIONING keys*

These keys are used to move the pen manually in any of the arrow directions (four directions) indicated on the keys. Pressing the two adjacent keys together moves it in a diagonal direction.

9. *FAST key*

Pressing this key together with a POSITIONING key increases the pen speed. Also pressing this key together with the ENTER key causes the X and Y coordinates to rotate 90 degrees.

10. *SCALING POINT keys [P1 and P2]*

Pressing the P1 or P2 key causes the pen to lift and move to set scaling point P1 or P2. When manually setting the scaling point, the ENTER key has to be used in conjunction with these keys.

11. *ENTER key*

Pressing the key together with the P1 or P2 key sets the scaling point of P1 and P2. Turning ON the power supply while pressing this key sets the self test mode.

12. *PAUSE key*

When this key is pressed once during program execution, PAUSE LED goes on and the plotting operation is temporarily halted. When the plotter starts to operate again, pressing this key once more causes the PAUSE LED to go off.

13. *VIEW key*

Pressing this key causes the pen to return to the pen stock and the pen carriage to move to the upper right position on the drawing board. Pressing this key together with ENTER key, resets the plotter just as if the power supply were turned on.

14. *PAPER HOLD key*

This key is for absorbing the plotter paper to the drawing board. Pressing it causes the paper to stick to the drawing board by means of the electrostatic paperholder.

15. *PEN SELECT keys*

The pen can be selected either by the operation panel or command; however the last designation has priority in pen selection. Pen speed can be set in combination with using PEN SPEED key. Pressing ENTER together with PEN SELECT returns the pen in the pen carriage to the designated pen stock. But if an occupied pen stock is designated, the pen in the pen carriage will hit it and malfunction will occur. In this case, reset the plotter by pressing the ENTER key together with the VIEW key.

16. *PEN SPEED key*

When setting the pen speed by the operation panel the PEN SELECT key also has to be used.

17. *PEN UP/PEN DOWN key*

When the plotter is at standby (including when the plotter is not operated programmably by computer or is in a test mode), pressing this key selects the pen-up or pen-down position. But if the pen is left in the pen-down condition for a certain period, the automatic pen-up system operates and the pen lifts.

18. *REPLOT MODE key*

If this key is pressed, the data buffer in the plotter will be cleared and the REPLOT MODE LED will light. Either drawing or replotting is possible in this status. However, if the buffer overflows the error LED will blink and replotting will be impossible.

19. *REPLOT key*

Pressing this key will replot the data from the time the REPLOT MODE key was pressed.

20. *POWER/ERROR LED*

If an error occurs, the indicator will blink. It displays errors both in commands and in computer communication conditions. This indicator is normally on when the power is on.

21. *X-Y Coordinate Display*

Displays the position of the pen carriage in the X-Y coordinate values.

APPENDIX A2

MAIN FEATURES OF THE PLOTTER

Drafting Speed

The DXY 1300 series is capable of drawing at a maximum speed of 420mm/sec, and this speed is selected at power on. The DXY 1300 series pen speed can be freely adjusted depending on the type of pen and paper to be used. The following show examples.

1. *Pen speed adjustment with control panel*

Press any of the pen select keys 1→8 while the PEN SPEED key on the control panel is being pressed to change the pen speed. The pen speed is set by each Pen select key is as follows

Pen No.	1	2	3	4	5	6	7	8
Pen speed (mm/sec)	30	40	60	90	120	160	220	420

Table A2. Possible pen speeds.

Also, the above operation can change the pen speed even in the middle of an operation after the PAUSE key is pressed. Therefore, use this method to slow the pen speed if the higher speeds are causing too much vibration to the plate.

2. *Pen speed adjustment with mode setting*

When the power is turned ON, the plotter is set to the normal mode (420 mm/sec). But if the power is turned ON while pressing the following keys, the pen speed appropriate for the pen in use can be set.

- OHP mode (100mm/sec)

This is set by turning ON the power while pressing the FAST key on the control panel. In this mode, the pen speed is 100mm/sec maximum.

- Ink pen mode (200mm/sec)

This is set by turning ON the power while pressing the position key ↓ on the control panel. In this mode, the speed is 200mm/sec maximum.

These two methods can be used on the plotter side without regard to the computer software. Thus, they are very useful if a commercial software program cannot be modified.

3. *Pen speed adjustment by programming*

Use of the pen speed setting command VS can change the pen speed within a drawing program. The setting of pen speed by command varies from 10mm/sec, which is the slowest, to 420mm/sec which is the fastest.

There is also the facility of adjusting the pen speed in AutoCAD. This option will be discussed in greater detail later on in this chapter.

Step Size

A 0.025mm step size is possible through using the Roland DXY 1300 plotter

APPENDIX B

SOFTWARE CONFIGURATION

From the software package there are five separate menu headings to choose from. Each of these headings in turn has a few different possibilities. In order to understand how to work this software package the first step is to explain what each heading does.

1. *FILE*

Save - The data obtained from a measurement can be saved to a data file for further use.

Open - This loads previously saved data into the program.

Exit - This is to exit the program. It is important to ensure that all the data is saved before exiting. Also quitting the program will automatically switch off the sensor.

2. *SENSOR*

Sensortype - The ILD 2000 series contains many different measuring ranges from 5 to 200mm. The purpose of this switch is to set the correct measuring range for the ILD 2005 of 5mm.

Power - This enables switching on and off the voltage to the sensor.

Average - The sensor ILD2000 is able to calculate a recursive mean over the recorded data. The number of the means can be varied by the user. The sensor notices the average in two ways:

a) In the short time memory (the number of averaging is stored in the RAM of the sensor). Using reset or switching off the power supply then the sensor forgets the value again.

b) In the long time memory (the averaging number is stored in the EEPROM of the sensor). This value will be activated with every reset or switch on of the sensor.

If the question "average save " after input of the average is answered with a "no", then the averaging number will reach only the "short time memory".

The change of average also effects the frequency limit of the sensor which is discussed further on.

3. *MEASURE*

Sensor 1 - This enables measurements to be taken by the sensor. Once in this mode you are given the option of either single shot or continuous measurement. There are certain parameters on display in this menu. They are the max. and min. values, the present value and the number of values recorded so far. For a single shot measurement we press the save button to record a value and the delete button to delete an unwanted measurement. If we are using continuous measurement we have to specify the sampling rate and the number of values to be recorded before starting the measurement process. As stated above there are limits set on the sampling rate and the number of values which can be stored to memory.

4. *DIAGRAM*

In the diagram option the data can be presented for one or two sensors or the result of the thickness measurement. The maximal number of the presented values is 8000,

but note that a great number of values will be compressed. As a result of this aliasing effects may occur.

The menu has the following points:

File - Under this menu point you may exit or print the presented diagram. The printer works under control of the WINDOWS print manager.

Zoom - Under this menu point you may scale up or down the cut-out in your diagram. The steps are 1/2, 1/10, 1/100, 2, 10, 100. The reduction or extension always acts on the just presented middle of the figure.

<<Figure>> - Using this menu point you may move your selected cut-out of the figure to the left or right in the value field.

Statistic Trend - You may compare the measurement with several statistical trends, which you can insert into the diagram.

These are the subsequent statistical trends:

Average trend

Min., Max.

Standard deviation

Linear regression

Curve fitting

With the menu point "delete" you may delete the called up statistic trends again.

Options - Here you may control the presentation of the diagram. With the "sign on", "sign off" it is possible to set a mark at every value recorded and to delete them again. "Grid on", "grid off" switches on and off the X and Y grid.

The Y-axis is automatically matched to the measuring range. However, if you want to choose a higher scale it is possible under the menu point "Y-axis". If you choose a

smaller scale, the diagram automatically matches to the greatest value. With the menu point "X-axis" you may select a section of the measured values.

5. *OPTIONS*

This menu helps set certain conditions before beginning the measuring process.

Trigger - The trigger is used to realise a defined start of the continuous measurement process. It is possible to pre-set some conditions for the start under the menu point "trigger". Before setting of the trigger conditions it is necessary to select the sensor type.

The subsequent trigger conditions are possible:

Trigger from infinity - Using this trigger condition it is possible to start the measurement with a jump from out of measuring range into the measuring range.

Trigger at - Using this trigger condition it is possible to start the measurement by a relative jump between two successive values in the data sequence. The trigger starts the measurement, if the difference of two successive values is higher than the predetermined value. The jump can be at any position in the measuring range.

Trigger from to - Using this trigger condition it is possible to start the measurement by an absolute jump in the data sequence. The jump results over a threshold, i.e. there must be a value smaller/higher than the predetermined value with the command "from" and after that a value higher/smaller than the predetermined value with the command "to".

Trigger smaller - Using this trigger condition it is possible to start the measurement by reaching an absolute low value.

Trigger higher - Using this trigger condition it is possible to start the measurement by reaching an absolute high value.

No Trigger - The measurement starts immediately after pushing the button. "No trigger" is the default installation.

Frequency limit - This allows us an examination over the effect of AVERAGES. Changing the averaging number effects the frequency limit of the sensor. It is possible to change certain parameters (No. of averages, 3dB frequency limit or 0.03% error frequency limit) from their preselected values to any other values. After selecting the parameters for their desired values, activate the button "Calculate" to continue the calculations. If you change the averaging number gives the 3dB frequency limit and the frequency limit for an error smaller than the non-linearity. Changing the 3dB frequency limit gives the averaging number. Finally changing the frequency limit for an error smaller than the non-linearity and you will get the averaging number as a result.

Decimal point presentation - It is possible to select the decimal sign '.'(decimal point) or ','(comma). This is useful for adapting the data for a later processing in other programs.

APPENDIX C

MACRO VISUAL BASIC PROGRAM

macshane Macro

Sub macshane()

With Toolbars(8)

Left = 269

Top = 65

End With

Range("S1:S159").Select

Selection.Cut

ActiveWindow.ScrollColumn = 1

Range("B2").Select

ActiveSheet.Paste

Application.Goto Reference:="R169C19"

Range("S160:S168").Select

Selection.Delete Shift:=xlUp

Range("S335").Select

ActiveWindow.SmallScroll Down:=-6

Range("S160:S318").Select

Range("S318").Activate

Selection.Cut

ActiveWindow.ScrollRow = 1

ActiveWindow.ScrollColumn = 1

Range("C2").Select

ActiveSheet.Paste

Application.Goto Reference:="R328C19"

Range("S319:S327").Select

Selection.Delete Shift:=xlUp

Range("S319:S477").Select
Selection.Cut
ActiveWindow.ScrollColumn = 1
ActiveWindow.ScrollRow = 1
Range("D2").Select
ActiveSheet.Paste
Application.Goto Reference:="R487C19"
Range("S478:S486").Select
Selection.Delete Shift:=xlUp
Range("S478:S636").Select
Selection.Cut
ActiveWindow.ScrollColumn = 1
ActiveWindow.ScrollRow = 12
ActiveWindow.ScrollRow = 1
Range("E2").Select
ActiveSheet.Paste
Application.Goto Reference:="R646C19"
Range("S637:S645").Select
Selection.Delete Shift:=xlUp
Range("S637:S795").Select
Selection.Cut
ActiveWindow.ScrollColumn = 1
ActiveWindow.ScrollRow = 1
Range("F2").Select
ActiveSheet.Paste
Application.Goto Reference:="R805C19"
Range("S796:S804").Select
Selection.Delete Shift:=xlUp
Range("S796:S954").Select
Selection.Cut
ActiveWindow.ScrollColumn = 1
ActiveWindow.ScrollRow = 1

```

Range("G2").Select
ActiveSheet.Paste
Application.Goto Reference:="R964C19"
Range("S955:S963").Select
Selection.Delete Shift:=xlUp
Range("S955:S1113").Select
Selection.Cut
ActiveWindow.ScrollRow = 1
ActiveWindow.ScrollColumn = 1
Range("H2").Select
ActiveSheet.Paste
Application.Goto Reference:="R1123C19"
Range("S1114:S1122").Select
Selection.Delete Shift:=xlUp
Range("S1114:S1272").Select
Selection.Cut
ActiveWindow.ScrollColumn = 1
ActiveWindow.ScrollRow = 1
Range("I2").Select
ActiveSheet.Paste
Application.Goto Reference:="R1282C19"
Range("S1273:S1281").Select
Selection.Delete Shift:=xlUp
Range("S1273:S1431").Select
Selection.Cut
ActiveWindow.ScrollRow = 1
ActiveWindow.ScrollColumn = 1
Range("J2").Select
ActiveSheet.Paste
Application.Goto Reference:="R1441C19"
Range("S1432:S1440").Select
Selection.Delete Shift:=xlUp

```

```

Range("S1432:S1590").Select
Selection.Cut
ActiveWindow.ScrollRow = 1
ActiveWindow.SmallScroll ToRight:=-1
Range("K2").Select
ActiveSheet.Paste
Application.Goto Reference:="R1600C19"
Range("S1591:S1599").Select
Selection.Delete Shift:=xlUp
Range("S1591:S1749").Select
Selection.Cut
ActiveWindow.ScrollRow = 1
Range("L2").Select
ActiveSheet.Paste
Application.Goto Reference:="R1759C19"
Range("S1750:S1758").Select
Selection.Delete Shift:=xlUp
Range("S1750:S1908").Select
Selection.Cut
ActiveWindow.ScrollRow = 1
Range("M2").Select
ActiveSheet.Paste
Application.Goto Reference:="R1918C19"
Range("S1909:S1917").Select
Selection.Delete Shift:=xlUp
Range("S1909:S2067").Select
Selection.Cut
ActiveWindow.ScrollRow = 1
Range("N2").Select
ActiveSheet.Paste
Application.Goto Reference:="R2077C19"
Range("S2068:S2076").Select

```

```

Selection.Delete Shift:=xlUp
Range("S2068:S2226").Select
Selection.Cut
ActiveWindow.ScrollRow = 1
Range("O2").Select
ActiveSheet.Paste
Application.Goto Reference:="R2236C19"
Range("S2227:S2235").Select
Selection.Delete Shift:=xlUp
Range("S2227:S2385").Select
Selection.Cut
ActiveWindow.ScrollRow = 1
Range("P2").Select
ActiveSheet.Paste
Application.Goto Reference:="R2395C19"
Range("S2386:S2394").Select
Selection.Delete Shift:=xlUp
Range("S2386:S2543").Select
Selection.Cut
ActiveWindow.ScrollRow = 1
Range("Q2").Select
ActiveSheet.Paste
ActiveWindow.SmallScroll ToRight:=-10
ActiveWindow.ScrollRow = 121
ActiveWindow.SmallScroll Down:=29
ActiveWindow.SmallScroll ToRight:=8
Range("Q161").Select
ActiveWindow.ScrollRow = 1
ActiveWindow.SmallScroll ToRight:=-8
End Sub

```


APPENDIX D

TABLE OF ALUMINIUM RESULTS

	A	B	C	D	E	F	G	H	I
1	-0.8889	-0.839	-0.8244	-0.844	-0.7956	-0.8394	-0.8221	-0.8694	-0.8872
2	-0.8771	-0.8361	-0.8265	-0.8388	-0.8049	-0.8363	-0.8142	-0.8657	-0.8852
3	-0.8904	-0.8412	-0.8326	-0.8424	-0.8124	-0.8404	-0.8195	-0.8584	-0.8788
4	-0.8836	-0.8399	-0.8323	-0.8282	-0.8269	-0.8567	-0.8282	-0.8633	-0.8788
5	-0.8803	-0.8413	-0.8461	-0.8248	-0.84	-0.8412	-0.8333	-0.849	-0.8784
6	-0.8669	-0.8227	-0.8481	-0.8199	-0.8274	-0.844	-0.8392	-0.8594	-0.8816
7	-0.8796	-0.8404	-0.8681	-0.8006	-0.8276	-0.839	-0.8359	-0.8744	-0.8863
8	-0.8828	-0.8347	-0.8516	-0.8292	-0.8098	-0.8269	-0.8328	-0.8673	-0.8889
9	-0.8858	-0.8426	-0.8598	-0.8264	-0.8157	-0.8142	-0.8343	-0.8852	-0.8926
10	-0.8824	-0.831	-0.8483	-0.826	-0.8443	-0.8248	-0.8249	-0.9011	-0.887
11	-0.8767	-0.8312	-0.8588	-0.8211	-0.8352	-0.8209	-0.8335	-0.8869	-0.8834
12	-0.8789	-0.8296	-0.8441	-0.8302	-0.8482	-0.8224	-0.836	-0.8877	-0.878
13	-0.8879	-0.8331	-0.8514	-0.8128	-0.8464	-0.8266	-0.8354	-0.8809	-0.8755
14	-0.8858	-0.8433	-0.8415	-0.8022	-0.8494	-0.8294	-0.8339	-0.8879	-0.8792
15	-0.8869	-0.8315	-0.862	-0.8151	-0.8489	-0.8327	-0.8307	-0.8861	-0.8903
16	-0.882	-0.8424	-0.8688	-0.809	-0.8541	-0.8286	-0.8408	-0.8914	-0.8865
17	-0.882	-0.8319	-0.8632	-0.8284	-0.8546	-0.8156	-0.8367	-0.8918	-0.8869
18	-0.8824	-0.8343	-0.8702	-0.812	-0.8386	-0.8204	-0.8437	-0.8906	-0.8889
19	-0.8752	-0.8416	-0.8698	-0.8372	-0.8524	-0.8138	-0.8412	-0.8872	-0.8959
20	-0.8913	-0.8381	-0.8528	-0.831	-0.8474	-0.827	-0.8406	-0.8852	-0.8925
21	-0.8869	-0.831	-0.8424	-0.7911	-0.8549	-0.8241	-0.8426	-0.878	-0.8865
22	-0.8738	-0.8263	-0.8346	-0.6932	-0.8555	-0.8315	-0.8388	-0.8851	-0.8908
23	-0.8794	-0.8335	-0.8319	-0.8008	-0.869	-0.8297	-0.8441	-0.8971	-0.8903
24	-0.8696	-0.8263	-0.8402	-0.807	-0.8624	-0.8296	-0.8469	-0.8926	-0.8978
25	-0.8692	-0.8321	-0.8384	-0.8378	-0.8735	-0.8426	-0.8496	-0.8994	-0.901
26	-0.8763	-0.8341	-0.8474	-0.8093	-0.8404	-0.8163	-0.8578	-0.8971	-0.9069
27	-0.8699	-0.8368	-0.8535	-0.7898	-0.8473	-0.8168	-0.8533	-0.904	-0.8993
28	-0.869	-0.8379	-0.869	-0.8177	-0.8343	-0.8164	-0.8537	-0.8955	-0.9
29	-0.8748	-0.8373	-0.8494	-0.7703	-0.8335	-0.8155	-0.8551	-0.8872	-0.9016
30	-0.862	-0.8457	-0.8661	-0.7638	-0.8324	-0.8159	-0.859	-0.89	-0.9017
31	-0.8599	-0.8313	-0.8697	-0.7963	-0.839	-0.8184	-0.8512	-0.8881	-0.9004
32	-0.8606	-0.84	-0.8493	-0.7817	-0.8579	-0.8226	-0.8566	-0.8849	-0.9013
33	-0.8494	-0.8359	-0.8691	-0.8121	-0.8573	-0.8257	-0.8468	-0.8937	-0.912
34	-0.8656	-0.8337	-0.8604	-0.7949	-0.8486	-0.8286	-0.8526	-0.8954	-0.8963
35	-0.8551	-0.8465	-0.8712	-0.7804	-0.8505	-0.8279	-0.8571	-0.8955	-0.9008
36	-0.855	-0.8379	-0.8521	-0.7806	-0.8526	-0.8251	-0.8635	-0.8951	-0.9057
37	-0.8577	-0.843	-0.8664	-0.7833	-0.8416	-0.8225	-0.8679	-0.9006	-0.9221
38	-0.8469	-0.8322	-0.8731	-0.78	-0.8439	-0.8342	-0.8698	-0.8985	-0.9193
39	-0.8476	-0.8149	-0.8632	-0.7813	-0.8418	-0.8148	-0.8671	-0.8893	-0.9122
40	-0.8533	-0.8193	-0.8492	-0.7935	-0.8404	-0.8204	-0.8676	-0.8872	-0.9186
41	-0.8431	-0.8024	-0.8489	-0.8017	-0.8421	-0.8308	-0.8666	-0.8888	-0.9102
42	-0.8521	-0.8168	-0.8356	-0.7984	-0.8547	-0.8324	-0.8565	-0.8825	-0.9171
43	-0.8477	-0.8105	-0.8451	-0.7877	-0.8559	-0.83	-0.8618	-0.8802	-0.9125
44	-0.844	-0.8166	-0.8487	-0.8028	-0.8694	-0.8335	-0.8694	-0.8816	-0.9154
45	-0.8531	-0.8399	-0.8499	-0.7951	-0.8483	-0.8243	-0.8675	-0.8834	-0.9268
46	-0.8603	-0.83	-0.8448	-0.7893	-0.8579	-0.8263	-0.8794	-0.8856	-0.9287
47	-0.8572	-0.84	-0.8571	-0.7919	-0.8519	-0.8149	-0.8677	-0.8861	-0.9282

	J	K	L	M	N	O	P	Q	R
1	-0.9255	-1.0252	-0.8901	-0.9144	-0.8549	-0.8579	-0.8661	-0.8954	-0.9727
2	-0.9252	-1.0241	-0.8845	-0.911	-0.8559	-0.8576	-0.8748	-0.9032	-0.9681
3	-0.9168	-1.0092	-0.8903	-0.9152	-0.8526	-0.8578	-0.871	-0.9084	-0.9826
4	-0.9181	-1.007	-0.8823	-0.9139	-0.8487	-0.86	-0.8681	-0.9061	-0.9844
5	-0.9109	-1.0104	-0.8732	-0.9138	-0.8592	-0.8583	-0.8583	-0.9097	-0.9937
6	-0.911	-1.0064	-0.8767	-0.9138	-0.86	-0.862	-0.8573	-0.9026	-0.9823
7	-0.9234	-1.0044	-0.8819	-0.9081	-0.8519	-0.8587	-0.8556	-0.896	-0.9865
8	-0.9304	-1.001	-0.8901	-0.9167	-0.8483	-0.8608	-0.8608	-0.9042	-0.9803
9	-0.9269	-1.0003	-0.8947	-0.9183	-0.8474	-0.8604	-0.8791	-0.9003	-0.9861
10	-0.9318	-1.0003	-0.9035	-0.8938	-0.8447	-0.8541	-0.8622	-0.8922	-0.9864
11	-0.9319	-0.9954	-0.9097	-0.8898	-0.855	-0.8601	-0.8641	-0.8953	-0.9958
12	-0.9363	-0.9973	-0.9014	-0.9	-0.8541	-0.849	-0.8657	-0.8985	-0.9943
13	-0.9405	-0.9999	-0.9	-0.8951	-0.845	-0.8482	-0.862	-0.8991	-0.985
14	-0.9545	-0.9843	-0.9032	-0.8929	-0.8514	-0.8474	-0.8615	-0.8926	-0.9951
15	-0.9652	-0.9705	-0.9032	-0.8967	-0.8547	-0.8669	-0.8591	-0.8979	-0.9857
16	-0.971	-0.9628	-0.8942	-0.8856	-0.855	-0.8686	-0.8561	-0.8963	-0.9826
17	-0.98	-0.9678	-0.9075	-0.8863	-0.8501	-0.8856	-0.8632	-0.9102	-0.9712
18	-0.9809	-0.9709	-0.9118	-0.8719	-0.8536	-0.8942	-0.8604	-0.9031	-0.9802
19	-0.9934	-0.9674	-0.9095	-0.8758	-0.8501	-0.8914	-0.8675	-0.9022	-0.9802
20	-0.9903	-0.9703	-0.922	-0.8824	-0.8559	-0.8689	-0.8684	-0.9131	-0.9882
21	-0.9811	-0.973	-0.911	-0.8809	-0.8485	-0.8651	-0.8685	-0.9153	-0.9806
22	-0.9854	-0.9779	-0.9138	-0.873	-0.8492	-0.8781	-0.8686	-0.9273	-0.9843
23	-0.9796	-0.9796	-0.9226	-0.8652	-0.854	-0.8751	-0.8622	-0.9244	-0.9808
24	-0.9771	-0.9882	-0.9178	-0.8739	-0.8465	-0.8763	-0.862	-0.9203	-0.97
25	-0.9857	-0.9778	-0.9285	-0.8715	-0.8443	-0.8636	-0.8639	-0.9303	-0.9536
26	-0.9993	-0.9775	-0.9335	-0.8642	-0.8456	-0.8658	-0.8641	-0.9309	-0.9503
27	-0.9967	-0.9817	-0.9307	-0.8758	-0.8487	-0.8681	-0.8573	-0.9392	-0.9491
28	-0.9974	-0.975	-0.9325	-0.8677	-0.8571	-0.8649	-0.8652	-0.9483	-0.9501
29	-0.9978	-0.9726	-0.9261	-0.8647	-0.8534	-0.8701	-0.87	-0.9484	-0.9543
30	-0.9865	-0.9512	-0.9358	-0.8751	-0.8521	-0.8669	-0.8646	-0.9463	-0.965
31	-0.9928	-0.9662	-0.9265	-0.8783	-0.855	-0.8717	-0.8671	-0.9565	-0.966
32	-0.984	-0.9978	-0.9284	-0.8693	-0.86	-0.8771	-0.8693	-0.9493	-0.9695
33	-0.9889	-1.0139	-0.9319	-0.8621	-0.86	-0.8717	-0.8707	-0.9542	-0.9688
34	-0.9946	-0.9925	-0.9312	-0.86	-0.8549	-0.8816	-0.8744	-0.9457	-0.967
35	-1.0003	-0.9921	-0.9307	-0.8618	-0.8579	-0.877	-0.873	-0.9462	-0.9726
36	-1.0002	-0.985	-0.9266	-0.8569	-0.862	-0.8709	-0.8669	-0.9452	-0.9522
37	-1.0018	-0.9503	-0.9228	-0.8571	-0.8589	-0.8742	-0.8702	-0.9519	-0.9641
38	-1.0044	-0.9526	-0.9242	-0.8447	-0.8604	-0.8802	-0.8755	-0.9452	-0.9617
39	-1.0105	-0.9811	-0.9102	-0.8632	-0.8612	-0.8783	-0.8824	-0.9437	-0.9444
40	-1.0027	-0.984	-0.9142	-0.8623	-0.8568	-0.8798	-0.8843	-0.949	-0.819
41	-1.0002	-0.8244	-0.9181	-0.8618	-0.856	-0.8804	-0.8852	-0.9469	-0.9219
42	-1.002	-0.8382	-0.9092	-0.8534	-0.8537	-0.87	-0.8829	-0.9489	-0.8171
43	-1.007	-0.8783	-0.9206	-0.8487	-0.8598	-0.8702	-0.8836	-0.9442	-0.8124
44	-1.0173	-0.8436	-0.9093	-0.8487	-0.8669	-0.862	-0.8773	-0.9517	-0.868
45	-1.0123	-0.8939	-0.9152	-0.8575	-0.8652	-0.875	-0.88	-0.956	-0.8893
46	-1.0121	-0.8985	-0.9127	-0.8572	-0.8662	-0.8675	-0.8922	-0.9682	-0.8794
47	-1.0184	-0.8919	-0.9202	-0.8675	-0.8679	-0.8722	-0.8933	-0.967	-0.9074

	S	T	U	V	W	X	Y	Z	AA
1	-0.8806	-0.9004	-0.8475	-0.8603	-0.8453	-0.8109	-0.8526	-0.8406	-0.8654
2	-0.8882	-0.9025	-0.8507	-0.8582	-0.8429	-0.8084	-0.8482	-0.829	-0.8759
3	-0.8041	-0.8968	-0.848	-0.86	-2.6315	-0.8008	-0.8502	-0.8401	-0.873
4	-0.8592	-0.8898	-0.8417	-0.8564	-2.6315	-0.7991	-0.8502	-0.8431	-0.8691
5	-0.8629	-0.8981	-0.84	-0.8568	-2.6315	-0.8068	-0.8504	-0.8242	-0.8702
6	-0.8678	-0.8938	-0.84	-0.8568	-0.8561	-0.8059	-0.8565	-0.8244	-0.8706
7	-0.8848	-0.8888	-0.8525	-0.865	-0.835	-0.8029	-0.87	-0.8099	-0.8702
8	-0.8679	-0.8975	-0.8519	-0.8559	-0.8362	-0.8118	-0.8745	-0.8048	-0.8673
9	-0.8802	-0.891	-0.849	-0.8539	-0.839	-0.8139	-0.8756	-0.799	-0.8615
10	-0.8872	-0.9048	-0.8514	-0.8482	-0.8362	-0.8167	-0.8732	-0.8074	-0.859
11	-0.8719	-0.899	-0.8451	-0.8625	-0.8347	-0.816	-0.8726	-0.8154	-0.8536
12	-0.8651	-0.8887	-0.8471	-0.8612	-0.8299	-0.8184	-0.8769	-0.8003	-0.8528
13	-0.8753	-0.8918	-0.8435	-0.8623	-0.8343	-0.8189	-0.8707	-0.9134	-0.8501
14	-0.8694	-0.8929	-0.845	-0.8601	-0.826	-0.8189	-0.8753	-0.8588	-0.8417
15	-0.8759	-0.8844	-0.8412	-0.8588	-0.8245	-0.8222	-0.8848	-0.8413	-0.8463
16	-0.878	-0.8916	-0.8501	-0.862	-0.8243	-0.8211	-0.888	-0.839	-0.8475
17	-0.8774	-0.9029	-0.8494	-0.8557	-0.8276	-0.8339	-0.8873	-0.8445	-0.848
18	-0.8907	-0.8926	-0.8425	-0.851	-0.8247	-0.8302	-0.8823	-0.8436	-0.8406
19	-0.8885	-0.8851	-0.8323	-0.8539	-0.8172	-0.817	-0.8855	-0.8363	-0.8399
20	-0.893	-0.8784	-0.849	-0.8511	-0.8228	-0.8185	-0.8851	-0.8336	-0.8514
21	-0.894	-0.8747	-0.8445	-0.8668	-0.8228	-0.8112	-0.8823	-0.8401	-0.8451
22	-0.8978	-0.872	-0.8438	-0.8566	-0.819	-0.8096	-0.8738	-0.8454	-0.8461
23	-0.8959	-0.8749	-0.8496	-0.8564	-0.8237	-0.8175	-0.8698	-0.8446	-0.8387
24	-0.8998	-0.8776	-0.8382	-0.853	-0.82	-0.8132	-0.8675	-0.8301	-0.8392
25	-0.8938	-0.8694	-0.8457	-0.8387	-0.8226	-0.8132	-0.8734	-0.8329	-0.8436
26	-0.9021	-0.869	-0.8506	-0.8339	-0.8248	-0.8168	-0.9163	-0.832	-0.8468
27	-0.9125	-0.8564	-0.8536	-0.8228	-0.8231	-0.8268	-2.6315	-0.8496	-0.8441
28	-0.9042	-0.8641	-0.8572	-0.8278	-0.8159	-0.8359	-2.6315	-0.8428	-0.8425
29	-0.907	-0.8649	-0.854	-0.8404	-0.8132	-0.8268	-2.6315	-0.84	-0.8365
30	-0.9071	-0.8642	-0.8573	-0.8433	-0.8098	-0.8152	-2.6315	-0.8399	-0.8299
31	-0.9035	-0.854	-0.8525	-0.8501	-0.8103	-0.8235	-2.6315	-0.8573	-0.8174
32	-0.9053	-0.8486	-0.8637	-0.8358	-0.8065	-0.8253	-2.6315	-0.8526	-0.8233
33	-0.9032	-0.8506	-0.8567	-0.8414	-0.8074	-0.8327	-2.6315	-0.8499	-0.8271
34	-0.9187	-0.8563	-0.8526	-0.8375	-0.8086	-2.6315	-2.6315	-0.8444	-0.8304
35	-0.9171	-0.8472	-0.8439	-0.8293	-0.8094	-2.6315	-2.6315	-0.8515	-0.8209
36	-0.9217	-0.8551	-0.8413	-0.8457	-0.8121	-2.6315	-0.8378	-0.8578	-0.8153
37	-0.9208	-0.8504	-0.8539	-0.8435	-0.8148	-2.6315	-0.844	-0.8557	-0.8103
38	-0.9167	-0.856	-0.8608	-0.8485	-0.8158	-2.6315	-0.8496	-0.8616	-0.8107
39	-0.9183	-0.8605	-0.8555	-0.8433	-0.8107	-2.6315	-0.8515	-0.8594	-0.8172
40	-0.9161	-0.8604	-0.8568	-0.8432	-0.806	-2.6315	-0.8282	-0.8684	-0.8076
41	-0.9189	-0.8503	-0.8578	-0.8472	-2.6315	-0.8544	-0.834	-0.8686	-0.8089
42	-0.9149	-0.8451	-0.8568	-0.8473	-2.6315	-0.8611	-0.8368	-0.8649	-0.8081
43	-0.9158	-0.8438	-0.8514	-0.8442	-2.6315	-0.8657	-0.8482	-0.8681	-0.8082
44	-0.9139	-0.8436	-0.8515	-0.8469	-2.6315	-0.8676	-0.8421	-0.8646	-0.7999
45	-0.9181	-0.8393	-0.8558	-0.8425	-2.6315	-0.8716	-0.8442	-0.869	-0.8071
46	-0.9173	-0.8468	-0.8584	-0.8436	-2.6315	-0.8683	-0.8461	-0.8713	-0.8008
47	-0.9129	-0.8403	-0.8575	-0.8461	-0.8128	-0.8665	-0.8584	-0.8647	-0.8099

	AB	AC	AD	AE	AF	AG	AH	AI	AJ
1	-0.8087	-0.8226	-0.848	-0.8318	-0.9149	-0.9392	-0.9822	-0.8873	-0.8443
2	-0.8064	-0.8215	-0.8522	-0.8343	-0.9131	-0.926	-0.9807	-0.8892	-0.84
3	-0.8073	-0.82	-0.8583	-0.8321	-0.9188	-0.9338	-0.9845	-0.8745	-0.8339
4	-0.7981	-0.8175	-0.8608	-0.8356	-0.9191	-0.9361	-0.9796	-0.8752	-0.8331
5	-0.7919	-0.8222	-0.8585	-0.8392	-0.9212	-0.9451	-0.9746	-0.8793	-0.8382
6	-0.7896	-0.8235	-0.8576	-0.842	-0.9212	-0.9337	-0.9783	-0.8768	-0.8417
7	-0.7927	-0.8237	-0.8551	-0.8345	-0.9281	-0.9339	-0.985	-0.8686	-0.836
8	-0.7934	-0.8257	-0.855	-0.8343	-0.9262	-0.9263	-0.9832	-0.8672	-0.837
9	-0.7896	-0.831	-0.856	-0.8314	-0.936	-0.9303	-0.9796	-0.8691	-0.8421
10	-0.7915	-0.8278	-0.8522	-0.8335	-0.9297	-0.9349	-0.9747	-0.8718	-0.8457
11	-0.7913	-0.831	-0.856	-0.8311	-0.9144	-0.9281	-0.9775	-0.8721	-0.8428
12	-0.7942	-0.8321	-0.8571	-0.835	-0.9235	-0.8812	-0.9893	-0.8638	-0.8473
13	-0.7905	-0.8285	-0.8558	-0.8325	-0.9297	-0.8436	-0.981	-0.8636	-0.8495
14	-0.792	-0.8315	-0.8505	-0.8286	-0.9375	-0.8777	-0.9754	-0.8635	-0.8447
15	-0.7926	-0.8343	-0.8561	-0.8331	-0.9347	-0.8477	-0.9744	-0.8567	-0.8502
16	-0.7997	-0.8378	-0.8499	-0.8285	-0.9324	-0.9379	-0.9682	-0.8471	-0.8487
17	-0.8028	-0.8393	-0.8524	-0.8368	-0.9399	-0.9391	-0.9687	-0.8475	-0.8501
18	-0.8049	-0.8439	-0.8525	-0.842	-0.942	-0.9543	-0.9658	-0.8479	-0.8495
19	-0.8044	-0.8388	-0.8494	-0.8467	-0.9433	-0.9854	-0.9563	-0.8461	-0.8491
20	-0.8021	-0.8394	-0.8446	-0.8502	-0.9513	-1.0203	-0.9515	-0.849	-0.8468
21	-0.7977	-0.8385	-0.84	-0.8505	-0.953	-0.9882	-0.9517	-0.8437	-0.8573
22	-0.809	-0.8379	-0.8433	-0.848	-0.9491	-0.9117	-0.9505	-0.8429	-0.8516
23	-0.8024	-0.8399	-0.8422	-0.8526	-0.9549	-0.9517	-0.9437	-0.8422	-0.8538
24	-0.7998	-0.8303	-0.8335	-0.8543	-0.9533	-0.9681	-0.9456	-0.8407	-0.8571
25	-0.7964	-0.8367	-0.8315	-0.8499	-0.9593	-0.9751	-0.9472	-0.8435	-0.8535
26	-0.7988	-0.834	-0.8336	-0.8493	-0.9563	-0.9614	-0.9413	-0.8451	-0.8624
27	-0.7988	-0.8444	-0.8357	-0.8529	-0.9508	-0.9634	-0.9347	-0.8473	-0.8645
28	-0.7887	-0.8414	-0.8342	-0.8521	-0.9558	-0.9634	-0.9235	-0.8467	-0.853
29	-0.798	-0.8361	-0.8321	-0.8578	-0.9628	-0.9767	-0.9374	-0.841	-0.8604
30	-0.7959	-0.8588	-0.8355	-0.8591	-0.9674	-0.9571	-0.9367	-0.8425	-0.8552
31	-0.8056	-0.8392	-0.8328	-0.8614	-0.9747	-0.9628	-0.9321	-0.8448	-0.8618
32	-0.7972	-0.8407	-0.8347	-0.8568	-0.9609	-0.9591	-0.9314	-0.8472	-0.8538
33	-0.799	-0.832	-0.8302	-0.8583	-0.962	-0.9675	-0.9281	-0.8396	-0.8611
34	-0.8029	-0.8504	-0.8267	-0.8601	-0.9584	-0.9665	-0.9367	-0.8412	-0.8604
35	-0.8116	-0.8408	-0.8323	-0.8558	-0.961	-0.9592	-0.9329	-0.8382	-0.8538
36	-0.8083	-0.8472	-0.8313	-0.8715	-0.9605	-0.9562	-0.9269	-0.8349	-0.8571
37	-0.8127	-0.8536	-0.8324	-0.8742	-0.9667	-0.9696	-0.9209	-0.8314	-0.858
38	-0.807	-0.8503	-0.8275	-0.8706	-0.9715	-0.9738	-0.9179	-0.8294	-0.8584
39	-0.8131	-0.8356	-0.8282	-0.8649	-0.9565	-0.9717	-0.9085	-0.8343	-0.8518
40	-0.8124	-0.8512	-0.8215	-0.8755	-0.962	-0.9658	-0.8955	-0.8367	-0.8491
41	-0.8077	-0.8507	-0.8206	-0.8861	-0.9648	-0.9775	-0.8991	-0.8307	-0.8599
42	-0.8051	-0.8492	-0.8243	-0.8872	-0.9547	-0.9768	-0.8986	-0.8324	-0.8706
43	-0.8045	-0.8521	-0.8268	-0.8944	-0.937	-0.9766	-0.9081	-0.8418	-0.8669
44	-0.8112	-0.8536	-0.827	-0.8936	-0.9256	-0.982	-0.9019	-0.8412	-0.864
45	-0.8085	-0.8579	-0.8313	-0.8916	-0.9374	-0.9792	-0.8912	-0.8417	-0.8589
46	-0.8135	-0.8571	-0.8314	-0.8985	-0.9265	-0.9766	-0.8845	-0.8401	-0.8705
47	-0.8184	-0.8522	-0.8318	-0.9095	-0.9285	-0.9773	-0.8849	-0.8441	-0.8613

	AK	AL	AM	AN	AO	AP	AQ	AR	AS
1	-0.863	-0.8847	-0.9773	-1.1611	-1.1314	-0.9935	-0.8798	-0.884	-0.8703
2	-0.8731	-0.8852	-0.9836	-1.1571	-1.1296	-0.9913	-0.884	-0.8863	-0.8755
3	-0.8731	-0.8837	-0.9901	-1.1474	-1.1253	-0.9913	-0.8856	-0.8889	-0.8746
4	-0.8708	-0.8858	-1.0028	-1.1467	-1.1255	-0.993	-0.8771	-0.8872	-0.8749
5	-0.8735	-0.8845	-1.0131	-1.1407	-1.1297	-0.9938	-0.8787	-0.885	-0.879
6	-0.8774	-0.8883	-1.0108	-1.1387	-1.1146	-0.9897	-0.8858	-0.8762	-0.8727
7	-0.8792	-0.8869	-1.0214	-1.1383	-1.1185	-0.9782	-0.8854	-0.8769	-0.8763
8	-0.882	-0.886	-1.0364	-1.1412	-1.1154	-0.9664	-0.8861	-0.8816	-0.872
9	-0.8836	-0.893	-1.0433	-1.1464	-1.112	-0.9688	-0.8841	-0.8759	-0.8671
10	-0.8831	-0.8971	-1.0484	-1.1586	-1.1118	-0.9726	-0.8837	-0.8788	-0.8629
11	-0.8824	-0.8932	-1.0537	-1.1525	-1.1121	-0.9719	-0.8868	-0.875	-0.8641
12	-0.8853	-0.8957	-1.059	-1.1413	-1.1206	-0.9634	-0.8853	-0.8795	-0.8697
13	-0.886	-0.9026	-1.07	-1.1515	-1.1242	-0.9497	-0.8788	-0.8759	-0.8645
14	-0.887	-0.9036	-1.0734	-1.1578	-1.1163	-0.9546	-0.8802	-0.8796	-0.8661
15	-0.888	-0.9057	-1.078	-1.1659	-1.1046	-0.9538	-0.8751	-0.8787	-0.8698
16	-0.8889	-0.911	-1.0798	-1.1626	-1.1051	-0.938	-0.8765	-0.8848	-0.876
17	-0.8849	-0.9076	-1.09	-1.1649	-1.1088	-0.944	-0.8737	-0.8898	-0.8783
18	-0.8906	-0.9043	-1.0983	-1.1764	-1.1088	-0.9408	-0.8834	-0.887	-0.8812
19	-0.8883	-0.9118	-1.0914	-1.1741	-1.1126	-0.936	-0.8862	-0.8923	-0.8767
20	-0.8906	-0.9159	-1.088	-1.1737	-1.0979	-0.9331	-0.8881	-0.8885	-0.8779
21	-0.8893	-0.9121	-1.0869	-1.0895	-1.1057	-0.931	-0.8851	-0.8912	-0.8801
22	-0.8832	-0.914	-1.0911	-1.0856	-1.102	-0.9294	-0.8851	-0.8923	-0.8833
23	-0.8942	-0.9173	-1.0939	-1.1018	-1.099	-0.933	-0.8845	-0.8962	-0.8819
24	-0.8867	-0.9236	-1.0901	-1.1212	-1.0962	-0.9203	-0.8884	-0.8904	-0.8887
25	-0.8885	-0.9248	-1.0941	-1.1289	-1.0857	-0.9118	-0.8873	-0.8947	-0.8866
26	-0.8914	-0.9305	-1.1002	-1.1159	-1.0806	-0.9021	-0.8859	-0.8919	-0.8808
27	-0.8963	-0.9312	-1.1074	-1.0941	-1.0737	-0.8979	-0.8879	-0.8918	-0.8792
28	-0.8902	-0.9457	-1.1034	-1.1002	-1.0687	-0.9024	-0.8904	-0.8935	-0.8809
29	-0.8888	-0.9456	-1.0991	-1.1061	-1.0666	-0.9044	-0.8938	-0.8926	-0.8817
30	-0.8921	-0.947	-1.1089	-1.1426	-1.067	-0.9058	-0.8898	-0.8946	-0.8911
31	-0.8918	-0.9432	-1.1178	-1.0568	-1.0633	-0.9015	-0.8923	-0.8902	-0.8941
32	-0.8883	-0.9442	-1.1163	-1.0502	-1.0598	-0.8986	-0.8862	-0.8936	-0.8904
33	-0.8884	-0.9537	-1.1148	-1.0936	-1.0603	-0.888	-0.886	-0.8877	-0.8883
34	-0.8799	-0.9473	-1.1191	-1.1431	-1.0664	-0.8916	-0.8934	-0.8826	-0.8936
35	-0.8813	-0.9578	-1.1264	-1.1334	-1.0555	-0.8955	-0.8935	-0.8776	-0.8951
36	-0.8828	-0.9566	-1.1284	-1.1304	-1.0427	-0.9026	-0.8926	-0.8808	-0.8978
37	-0.8869	-0.9526	-1.1252	-1.136	-1.0374	-0.9088	-0.8909	-0.8831	-0.8966
38	-0.8831	-0.9609	-1.1235	-1.1337	-1.0511	-0.8988	-0.8947	-0.8825	-0.9058
39	-0.8868	-0.9622	-1.1317	-1.13	-1.0341	-0.888	-0.8937	-0.8757	-0.913
40	-0.8873	-0.959	-1.146	-1.1218	-1.0341	-0.891	-0.894	-0.8757	-0.9234
41	-0.889	-0.9589	-1.1402	-1.1349	-1.0304	-0.8947	-0.8904	-0.8774	-0.9258
42	-0.8942	-0.9628	-1.1353	-1.1328	-1.0311	-0.8928	-0.8902	-0.8743	-0.9331
43	-0.8916	-0.9701	-1.1537	-1.1198	-1.0321	-0.89	-0.8894	-0.8723	-0.942
44	-0.8824	-0.9611	-1.1595	-1.1093	-1.0244	-0.882	-0.8876	-0.8661	-0.938
45	-0.8877	-0.9729	-1.1559	-1.1018	-1.0255	-0.8875	-0.884	-0.8683	-0.9417
46	-0.8906	-0.9763	-1.1589	-1.1107	-1.0136	-0.8788	-0.8829	-0.8709	-0.938
47	-0.889	-0.986	-1.1614	-1.1259	-1.0025	-0.8787	-0.8891	-0.87	-0.9411

	AT	AU	AV	AW	AX	AY	AZ	BA	BB
1	-0.9434	-1.1344	-0.9607	-0.899	-0.7674	-0.8392	-0.801	-0.7955	-0.9466
2	-0.9477	-1.1545	-0.9575	-0.8971	-0.7725	-0.8401	-0.7987	-0.8039	-0.9609
3	-0.9501	-1.1626	-0.9564	-0.8893	-0.7758	-0.8407	-0.7941	-0.801	-0.9693
4	-0.9554	-1.1557	-0.9451	-0.8877	-0.784	-0.8428	-0.7909	-0.7984	-0.9671
5	-0.9617	-1.1548	-0.9473	-0.8848	-0.7785	-0.8428	-0.7811	-0.7952	-0.9648
6	-0.9669	-1.1636	-0.9437	-0.8843	-0.7719	-0.8468	-0.7787	-0.8084	-0.9713
7	-0.9714	-1.1699	-0.9465	-0.8802	-0.77	-0.8415	-0.7795	-0.8142	-0.972
8	-0.9811	-1.1733	-0.9433	-0.8698	-0.7752	-0.8443	-0.7796	-0.8138	-0.9714
9	-0.9871	-1.165	-0.962	-0.869	-0.7693	-0.85	-0.7829	-0.8061	-0.9611
10	-0.9836	-1.1612	-0.9631	-0.8605	-0.7668	-0.8468	-0.7751	-0.8237	-0.9789
11	-0.9892	-1.1579	-0.9616	-0.8555	-0.7665	-0.85	-0.7765	-0.8258	-0.9895
12	-0.9935	-1.1586	-0.9664	-0.8567	-0.7755	-0.8526	-0.7772	-0.8186	-0.9982
13	-1.0001	-1.1538	-0.9606	-0.8504	-0.7798	-0.851	-0.7768	-0.8241	-0.9947
14	-1.0085	-1.1508	-0.9695	-0.8463	-0.776	-0.8487	-0.7727	-0.8283	-0.9896
15	-1.0108	-1.1399	-0.9617	-0.849	-0.7764	-0.8492	-0.7694	-0.8303	-0.9923
16	-1.0157	-1.1394	-0.9624	-0.8415	-0.7843	-0.8439	-0.7682	-0.8297	-0.9948
17	-1.0191	-1.1374	-0.964	-0.8354	-0.7853	-0.84	-0.7747	-0.8282	-0.9966
18	-1.027	-1.1347	-0.9648	-0.8374	-0.783	-0.8424	-0.7661	-0.8401	-0.9949
19	-1.0362	-1.1463	-0.9575	-0.8392	-0.7785	-0.8296	-0.7649	-0.8455	-0.9978
20	-1.0459	-1.1541	-0.9521	-0.8335	-0.7822	-0.8428	-0.7618	-0.8468	-1.0094
21	-1.0492	-1.1569	-0.9518	-0.8281	-0.7851	-0.8349	-0.7621	-0.8473	-1.0058
22	-1.0651	-1.1545	-0.9567	-0.8196	-0.7859	-0.8354	-0.7629	-0.8556	-0.9999
23	-1.072	-1.1705	-0.9581	-0.8192	-0.7945	-0.8345	-0.7637	-0.8642	-0.9803
24	-1.072	-1.1773	-0.9487	-0.8171	-0.7813	-0.8375	-0.7531	-0.8753	-0.9536
25	-1.069	-1.1826	-0.9602	-0.8103	-0.7909	-0.8433	-0.7603	-0.8723	-0.9673
26	-1.0732	-1.18	-0.9543	-0.8149	-0.7923	-0.8404	-0.7625	-0.8853	-0.9643
27	-1.0707	-1.179	-0.9501	-0.8102	-0.7947	-0.8382	-0.7686	-0.8919	-0.9546
28	-1.0667	-1.179	-0.9513	-0.8095	-0.8016	-0.839	-0.7651	-0.9022	-0.9691
29	-1.0592	-1.1804	-0.9494	-0.8077	-0.8033	-0.836	-0.7631	-0.906	-0.9799
30	-1.0625	-1.0476	-0.9557	-0.8031	-0.8041	-0.8361	-0.7606	-0.899	-0.9794
31	-1.0782	-1.028	-0.9531	-0.7923	-0.8113	-0.84	-0.7666	-0.9072	-0.9746
32	-1.0854	-1.0621	-0.9549	-0.7913	-0.8074	-0.8353	-0.7689	-0.9142	-0.9629
33	-1.0835	-1.0806	-0.9444	-0.7861	-0.8098	-0.836	-0.7699	-0.9207	-0.9765
34	-1.0897	-1.0823	-0.9403	-0.7761	-0.811	-0.8322	-0.7662	-0.9167	-0.9934
35	-1.0976	-1.0718	-0.9336	-0.7742	-0.8153	-0.8318	-0.7687	-0.9208	-0.9882
36	-1.0971	-1.0541	-0.9343	-0.7814	-0.8171	-0.8251	-0.7634	-0.9315	-0.9816
37	-1.0978	-1.0582	-0.9309	-0.7719	-0.8207	-0.8228	-0.7542	-0.9267	-0.9897
38	-1.1003	-1.0521	-0.9252	-0.7795	-0.8248	-0.827	-0.761	-0.9252	-0.9954
39	-1.1093	-1.0166	-0.9214	-0.7751	-0.826	-0.8253	-0.7611	-0.9157	-0.9944
40	-1.1211	-0.9074	-0.9228	-0.7682	-0.8241	-0.8248	-0.7752	-0.9191	-0.923
41	-1.1276	-0.9722	-0.9212	-0.7634	-0.8249	-0.82	-0.7704	-0.9301	-0.9269
42	-1.1353	-0.9509	-0.924	-0.7667	-0.8253	-0.8217	-0.764	-0.9238	-0.9273
43	-1.1337	-0.9788	-0.9101	-0.758	-0.8331	-0.819	-0.7649	-0.9283	-0.9444
44	-1.1419	-0.9709	-0.9196	-0.7726	-0.8339	-0.8122	-0.7732	-0.9286	-0.9772
45	-1.1421	-0.9644	-0.9203	-0.7715	-0.8358	-0.8125	-0.7761	-0.9428	-0.9571
46	-1.1333	-0.9563	-0.9109	-0.7756	-0.8371	-0.8106	-0.7772	-0.942	-0.972
47	-1.1304	-0.9558	-0.9012	-0.7788	-0.8396	-0.8042	-0.787	-0.9437	-0.9925

	BC	BD	BE	BF	BG	BH	BI	BJ	BK
1	-0.9451	-0.9413	-0.9475	-0.9362	-0.8657	-0.8127	-0.7606	-0.7588	-0.7713
2	-0.9123	-0.9368	-0.9485	-0.9251	-0.8632	-0.8148	-0.7549	-0.7596	-0.7679
3	-0.994	-0.9444	-0.9501	-0.9073	-0.8672	-0.8003	-0.7522	-0.7527	-0.764
4	-0.9547	-0.9531	-0.9456	-0.8965	-0.8713	-0.8045	-0.7536	-0.7506	-0.7693
5	-0.98	-0.9565	-0.9485	-0.9018	-0.8625	-0.8022	-0.7556	-0.7518	-0.7713
6	-0.975	-0.9693	-0.9462	-0.9005	-0.8474	-0.7987	-0.7577	-0.761	-0.7744
7	-0.9659	-0.9751	-0.9505	-0.8908	-0.8439	-0.7998	-0.7559	-0.7523	-0.7698
8	-0.9685	-0.983	-0.9347	-0.8918	-0.8469	-0.7919	-0.7545	-0.7491	-0.7759
9	-0.9646	-0.9584	-0.9419	-0.9104	-0.8392	-0.789	-0.7478	-0.7465	-0.777
10	-0.9675	-0.9475	-0.9335	-0.9148	-0.838	-0.7874	-0.7433	-0.7542	-0.788
11	-0.9565	-0.9458	-0.9342	-0.9125	-0.8357	-0.7842	-0.7457	-0.7467	-0.7876
12	-0.9529	-0.9559	-0.9322	-0.9022	-0.8318	-0.774	-0.7529	-0.7451	-0.792
13	-0.9608	-0.9657	-0.9312	-0.9008	-0.8127	-0.7747	-0.7503	-0.7546	-0.7947
14	-0.9546	-0.9503	-0.9326	-0.8876	-0.8087	-0.7682	-0.7589	-0.7574	-0.7935
15	-0.9473	-0.9457	-0.93	-0.8806	-0.819	-0.767	-0.7487	-0.7727	-0.8

Table D1. Aluminium experimental results