EFFECT OF SURFACE ROUGHNESS ON ULTRASONIC TESTING

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ABSTRACT

EFFECT OF SURFACE ROUGHNESS ON ULTRASONIC TESTING

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This study investigates the effect of front surface roughness on ultrasonic echo amplitude. Experiments were carried out on specimens whose front surfaces are machined by milling machine. Machining parameters were changed in milling process in order to obtain desired roughness values and milling head was tilted to a very small angle to obtain periodic rough surfaces. Experiments were performed with these specimens having roughness value of 0.5, 4.5, 11, 26.5 μm. Ra. The back surface roughness of all specimens was kept constant at 1.5 μm Ra by grinding operation. 1.5, 2, 3, 4 mm. holes were drilled at constant depth and to same side of each specimen to represent reference discontinuities. Ultrasonic tests, using pulse-echo technique were carried out to monitor echo amplitudes corresponding to different roughness values. The tests were also repeated by using different ultrasonic probes having different frequencies. For additional comparison, different couplants were used through the tests. The results showed that there was a significant increase in the reduction of the sound pressure level with the increase in the surface roughness. Although there was no uncertainty observed about not being able to detect discontinuity because of roughness but correct couplant and frequency selection has a positive effect on correctly sizing the discontinuity and at attenuation measurements. The results obtained with this work can be used as a guide for testing rough surfaces, predicting the effect on ultrasonic examination before testing and discontinuity detecting capability under rough surface conditions.

Keywords: Ultrasonic testing, surface roughness, effect of roughness, roughness measurement

ÖZ

YÜZEY PÜRÜZLÜLÜĞÜNÜN ULTRASONİK MUAYENEYE ETKİSİ

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Bu çalışmada, yüzey pürüzlülüğünün ultrasonik yankı yüksekliğine olan etkisi incelenmiştir. Deneyler, üst yüzeyi freze ile işlenmiş numuneler üzerinde yapılmıştır. İstenilen yüzey pürüzlülüğü değerleri, freze tezgahının parametreleri değiştirilerek işleme yapılmasıyla sağlanmış, freze kafasının küçük bir açıyla eğilmesiyle de yüzeylerde düzenli pürüzlülük elde edilmiştir. Deneyler, 0.5, 4.5, 11, 26.5 μm. Ra pürüzlülük değerlerine sahip numuneler üzerinde gerçekleştirilmiştir. Bütün numunelerin arka yüzeyleri, taşlanarak 1.5 μm Ra pürüzlülük değerine getirilmiştir. Her numunenin yan yüzeyinde, sabit derinliğe, 1.5, 2, 3, 4 mm çaplarında delikler açılarak bunların yapay hataları referans etmesi amaç edilmiştir. Darbe-yankı tekniği kullanılarak farklı pürüzlük değerlerine karşılık gelen yankı yükseklikleri incelenmiştir. Testler, değişik frekanslardaki ultrasonik problar kullanılarak tekrarlanmıştır. İlave bir karşılaştırma yapabilmek için de testler iki ayrı couplant kullanılarak tekrarlanmıştır. Sonuçlar, yüzey pürüzlülüğündeki artışın ses demeti basıncının azalmasına yol açtığını açıkça ortaya koymuştur. Her ne kadar, yüzey pürüzlülüğü dolayısıyla referans hataların tespit edilememesi gibi bir durumla karşılaşılmamış olsa da, uygun frekans ve couplant seçiminin, hataların ölçümlendirilmesinde ve ses zayıflaması ölçümlerindeki pozitif etkisi gözlemlenmiştir. Bu çalışmadan elde edilen sonuçlar, pürüzlü yüzeyleri test etmekte, olası etkileri test öncesi tahmin etmekte ve pürüzlü yüzeye sahip parçalardaki hatanın belirlenebilirliğinde bir rehber olarak kullanılabilir.

Anahtar kelimeler: Yüzey pürüzlülüğü, ultrasonik test, pürüzlülüğün etkisi, pürüzlük ölçümü

To my Parents

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CHAPTER 1

INTRODUCTION

Ultrasonic nondestructive testing is a versatile technique that can be applied to a wide variety of material analysis applications. While ultrasonic NDT is perhaps better known in its more common applications for thickness gauging, flaw detection, and acoustic imaging, whereas high frequency sound waves can also be used to discriminate and quantify some basic mechanical, structural, or compositional properties of solids and liquids. From this point of view, it can be seen that the use of ultrasound is well established as a NDT tool, and too many information can be obtained about the specimen being tested by using ultrasonic inspection.

On the other hand in every stage of life we are facing with some imperfections. This could be anything depending on the subject. But the fact is that, these imperfections are the nature themselves. Roughness is the nature of surfaces. In some applications you can make use of it (i.e. braking principle etc.) but whereas it may be a major problem standing against us in another application like in ultrasonic testing.

The reason is the condition of a test surface through which sound beam enters the material affects the amplitude, path and characteristics of the beam. The detectability of discontinuities such as cracks, voids, etc. is greatly affected by the extent of roughness. Increase in roughness reduces the transmitted energy of the sound beam and reduces the amplitude of the received signal. The necessity of taking surface roughness in to consideration can be given as

- Condition of test pieces: Before every testing, calibration of the instrument is done using standardized calibration blocks. But it is known that, in real life there is a strong possibility of not having the same conditions at test pieces that calibration blocks have.

- Difficulty of preparing the surface to the required condition: It is known that roughness can be reduced by some machining operations like grinding,

shaping, milling or other operations depending on the material, dimension, and availability to machining. But in some cases, preparation of the surface to the required test conditions may not be so easy. Because reducing roughness means more manpower, machining, time and cost. So it may be sometimes impractical or uneconomical to have surfaces with smooth finish for ultrasonic testing to achieve minimum loss of energy at the entry surface and maximum discontinuity detection sensitivity.

- Change in the surface quality between two test periods. If a piece has to be tested periodically or has to be retested later, surface condition may not be the same in each test.

So, all these may cause unpredictable results in testing like incorrect discontinuity sizing, locating and material structure. By this point of view, without considering surface roughness our results may be unreliable and misleading.

On the other hand, if, how the acoustical structure behaves is known when it faces with a rough surface and built a correlation between roughness and acoustical properties, than it may be possible to predict how test results of the ultrasonic inspection will be affected without altering the surface quality.

This study is based on this consideration. Several tests were made during this study to determine a correlation between roughness and ultrasonic inspection data. The specimens were prepared from commonly used industrial structure material AISI 1040 Steel. The results obtained from this study may be used for better estimation of the discontinuities at test pieces having rough front surface structure. Also this study can be used as a guideline for proper selection of the transducer frequency

CHAPTER 2

ULTRASONIC TESTING

2.1 Historical Review of NDT and Ultrasonic Testing

Nondestructive testing has been practiced for many decades, with initial rapid developments in instrumentation encouraged by the technological advances that occurred during World War II and the subsequent defense effort. During the earlier days, the primary purpose was the detection of defects. As a part of "safe life" design, it was intended that a structure should not develop macroscopic defects during its life, with the detection of such defects being a cause for removal of the component from service. In response to this need, increasingly sophisticated techniques using ultrasonics, eddy currents, x-rays, dye penetrants, magnetic particles, and other forms of interrogating energy emerged.

The first patent for using ultrasonic waves, using two transducers to detect flaws in solids was taken by Mulhauser, in 1931. Firestone (1940) and Simons (1945) developed pulsed ultrasonic testing using a pulse-echo technique.

The continued improvement of the technology, in particular its ability to detect small flaws, led to the unsatisfactory situation that more and more parts had to be rejected, even though the probability of failure had not changed. Then a new challenge was thus presented to the nondestructive testing community. Detection was not enough. One needed to also obtain quantitative information about flaw size to serve as an input to fracture mechanics based predictions of remaining life. These concerns, which were felt particularly strongly in the defense and nuclear power industries, led to the creation of a number of research programs around the world and the emergence of quantitative nondestructive evaluation (QNDE) as a new discipline. In the ensuing years, many important advances have been made. Quantitative theories have been developed to describe the interaction of the interrogating fields with flaws. Models incorporating the results have been integrated with solid model descriptions of real-part geometries to simulate practical inspections. Related tools allow NDE to

be considered during the design process on an equal footing with other failure-related engineering disciplines. Quantitative descriptions of NDE performance, such as the probability of detection (POD), have become an integral part of statistical risk assessment. Measurement procedures initially developed for metals have been extended to engineered materials, such as composites, where anisotropy and inhomogeneity have become important issues. The rapid advances in digitization and computing capabilities have totally changed the faces of many instruments and the type of algorithms that are used in processing the resulting data. High-resolution imaging systems and multiple measurement modalities for characterizing a flaw have emerged. Interest is increasing not only in detecting, characterizing and sizing defects, but in characterizing the materials in which they occur. Goals range from the determination of fundamental microstructural characteristics such as grain size, porosity and texture (preferred grain orientation) to material properties related to such failure mechanisms as fatigue, creep, and fracture toughness--determinations that are sometimes quite challenging to make due to the problem of competing effects.

2.2 Basic Acoustical Principles

Mechanical vibrations can propagate in solids, liquids and gasses. The actual particles of matter vibrate, and if the mechanical movements of the particles have regular motion, the vibrations can be assigned a frequency in cycles per second, measured in Hertz (Hz) where 1 Hz = 1 cycle per second. If this frequency is within the approximate range 10 to 20 000 Hz, the sound is audible. Sound generated above the human hearing range (above 20 kHz) is called ultrasound. However, the frequency range normally employed in ultrasonic nondestructive testing and thickness gaging is 100 KHz to 50MHz. Although ultrasound behaves in a similar manner to audible sound, it has a much shorter wavelength. This means it can be reflected off very small surfaces such as defects inside materials. It is this property that makes ultrasound useful for nondestructive testing of materials. The Acoustic Spectrum in Fig. 2.1 breaks down sound into 3 ranges of frequencies. The Ultrasonic Range is then broken down further into 3 sub sections. [2]

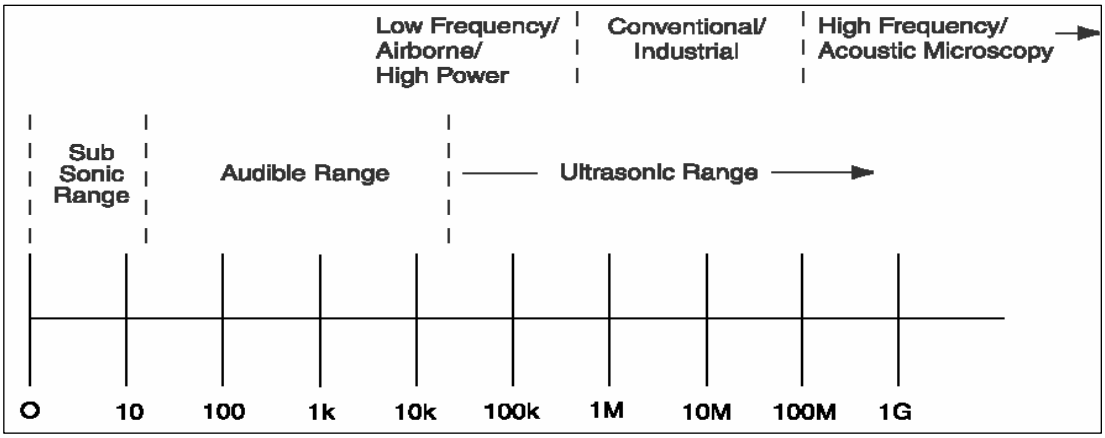


Fig.2.1: The Acoustic Spectrum

Frequency, Period and Wavelength

Ultrasonic vibrations travel in the form of a wave, similar to the way the light travels. However, unlike light waves, which can travel in an empty space, ultrasound requires an elastic medium such as a liquid or a solid. The basic parameters of a continuous wave (cw) which include the wavelength (λ) and the period (T) of a complete cycle are shown at Fig. 2.2.

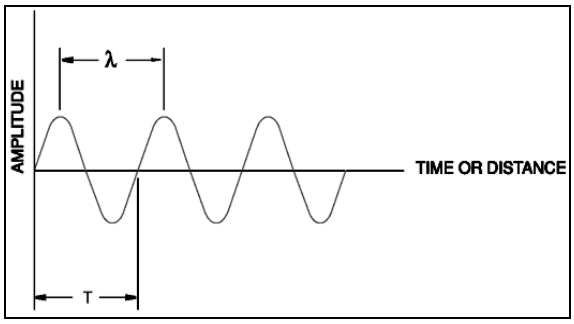


Fig. 2.2 Basic Parameters

As it is told above, the number of cycles completed in one second is called frequency and is measured in hertz. The time required to complete a full cycle is the period (T), measured in seconds. The relation between frequency and period in a continuous wave is given as;

$$f = \frac{1}{T} \qquad \text{(Eq. 2.1)}$$

The velocity of ultrasound (c) in a perfectly elastic material at a given temperature and pressure is constant. The relation between c, f, λ and T is given by

$$\lambda = \frac{c}{f} \qquad \text{(Eq. 2.2)} \qquad\qquad \lambda = c \cdot T \qquad \text{(Eq. 2.3)}$$

In Appendix A**,** you can see the list of longitudinal and shear wave velocities of materials commonly tested with ultrasonics

2.3 Wave Propagation

Ultrasonic testing is based on time-varying deformations or vibrations in materials, which is generally referred to as acoustics. All material substances are comprised of atoms, which may be forced into vibrational motion about their equilibrium positions. Many different patterns of vibrational motion exist at the atomic level, however, most are irrelevant to acoustics and ultrasonic testing. Acoustics is focused on particles that contain many atoms that move in harmony to produce a mechanical wave. Provided a material is not stressed in tension or compression beyond its elastic limit, its individual particles perform elastic oscillations. When the particles of a medium are displaced from their equilibrium positions, internal (electrostatic) forces arise. It is these elastic restoring forces between particles, combined with inertia of the particles that leads to oscillatory motions of the medium.

In solids, sound waves can propagate in four principle modes that are based on the way the particles oscillate. Sound can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves. Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing. The particle movement responsible for the propagation of longitudinal and shear waves is illustrated below. [1]

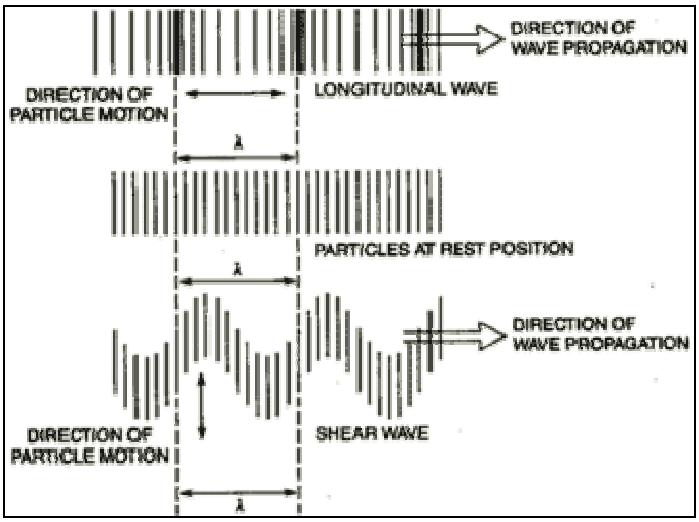


Fig.2.3 The Particle Movement of longitudinal and shear waves

In longitudinal waves, the oscillations occur in the longitudinal direction or the direction of wave propagation. Since compressional and dilatational forces are active in these waves, they are also called pressure or compressional waves. They are also sometimes called density waves because their particle density fluctuates as they move. Compression waves can be generated in liquids, as well as solids because the energy travels through the atomic structure by a series of comparison and expansion (rarefaction) movements.

In the transverse or shear wave, the particles oscillate at a right angle or transverse to the direction of propagation. Shear waves require an acoustically solid material for effective propagation and, therefore, are not effectively propagated in materials such as liquids or gasses. Shear waves are relatively weak when compared to longitudinal waves In fact, shear waves are usually generated in materials using some of the energy from longitudinal waves.

2.4 Types of Sound Wave Propagation

In air, sound travels by compression and rarefaction of air molecules in the direction of travel. However, in solids, molecules can support vibrations in other directions, hence, a number of different types (modes) of sound waves are possible. As mentioned previously, longitudinal and transverse (shear) waves are the most often

used in ultrasonic inspection. However, at surfaces and interfaces, various types of elliptical or complex vibrations of the particles make other waves possible. Some of these wave modes such as Rayleigh and Lamb waves are also useful for ultrasonic inspection. Some wave types and their particle vibration is given at Table 2.1

Table 2.1: Some of the wave types possible in solids [1]

Wave Types in Solids	**Particle Vibrations**
Longitudinal	Parallel to wave direction
Transverse (Shear)	Perpendicular to wave direction
Surface - Rayleigh	Elliptical orbit - symmetrical mode
Plate Wave - Lamb	Component perpendicular to surface (extensional wave)
Plate Wave - Love	Parallel to plane layer, perpendicular to wave direction
Stoneley (Leaky Rayleigh Waves)	Wave guided along interface
Sezawa	Antisymmetric mode

Rayleigh waves travel the surface of a relative thick solid material penetrating to a depth of one wavelength. Rayleigh waves are useful because they are very sensitive to surface defects and since they will follow the surface around, curves can also be used to inspect areas that other waves might have difficulty reaching.

Lamb waves, also known as plate waves, can be propagated only in very thin metals. Lamb waves are a complex vibrational wave that travels through the entire thickness of a material. Lamb waves provide a means for inspection of very thin materials. Propagation of Lamb waves depends on density, elastic, and material properties of a component, and they are influenced by a great deal by selected frequency and material thickness.

2.5 Elastic Properties of Solids

Within a freely vibrating medium, both inertial and elastic restoring forces act upon each particle. The interplay of these forces produce oscillatory motions in a manner analogous to the free vibration of a macroscopic system of masses and springs. Thus, the elastic restoring forces in a medium may be described as microscopic "spring" forces.

This concept follows Hook's Law, which states that, "within the elastic limit of any body, the ratio of the stress to the strain produced is constant. Simply speaking, this means that the more stress or force placed on an object, the more it will strain or deform. The "springs" model also obeys Newton's second law, which states that the force (F) equals the mass (m) times the acceleration (a), F = ma. Rewritten as F = kx, a formula that also follows Hook's Law. The spring model makes accurate predictions for the propagation of sound.

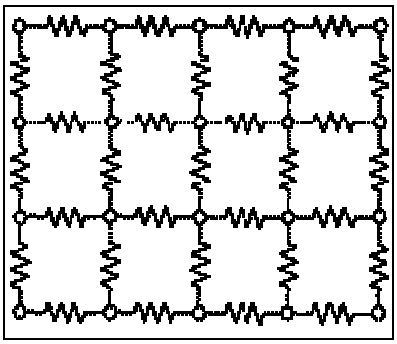


Fig. 2.4 Model of an elastic body

Sound wave propagation velocity is determined by material properties: elastic constants, C_{ij}, and material density, ρ. The velocity of a longitudinal wave is described by the following equation:

$$V_1 = \left(\frac{c_{11}}{\rho} \right)^{1/2} \qquad \text{(Eq. 2.4)}$$

where "c_{11}" is the elastic constant governing the oscillatory motion in the direction of wave propagation.

Shear (transverse) wave velocity can be written as;

$$V_S = \left(\frac{c_{44}}{\rho} \right)^{1/2} \qquad \text{(Eq. 2.5)}$$

where "c_{44}" is the elastic constant governing the oscillatory motion in the transverse direction. [1]

The longitudinal and shear wave speeds of some common materials are listed in Appendix A.

2.6 Attenuation of Sound Waves

An acoustic wave traveling through materials will lose energy for a variety of reasons. This behavior can account for a loss in amplitude as well as change in its appearance. There are three basic processes that account for loss of pulse energy, namely, beam spreading, absorption and scattering.

Beam spreading is primarily a geometric function where the intensity is decreasing with the square of the distance traveled. This may be observed by nothing that the initial pulse energy is being distributed over a larger spherical area as the wave front advances.

Absorption accounts for mechanical energy converted to heat energy as the wave front passes. Essentially, this energy is permanently lost and this type of attenuation is not of much use in materials inspection.

Scattering results from reflections at grain boundaries, small cracks, surface roughness and other material non-homogeneities. Material contains boundaries on which the acoustic impedance changes abruptly because two materials of different density or sound velocity meet at these interfaces. This phenomenon may account for serious energy losses which can render an item uninspectable. On the other hand, it may be useful in material studies where, for example, there is a need to measure grain size in metals or surface roughness by using ultrasound.

Attenuation is generally expressed in the form

$$P = P_0 \cdot e^{-a \cdot L} \qquad \text{(Eq. 2.6)}$$

where P = Pressure level at second reference location

P_0 = Original pressure level at a source or other reference location

a = Attenuation coefficient

L = Distance of pulse travel from original source to second reference location

Ultrasonic pulse attenuation is typically expressed in units of decibels (dB). Decibels are based on logarithmic scale and are convenient unit to use when the magnitude of the parameter being measured varies over a very large range. Ultrasonic pulses decay rather rapidly, due to the processes just described.

The relative sound pressure level (SPL) of a propagating wave is

$$SPL = 20 \cdot \log \frac{P}{P_0} \quad dB \qquad \text{(Eq. 2.7)}$$

where P is the effective pressure of ultrasonic wave at some observation point, and P_0 is the previous pressure at an earlier reference point. Considering two points in the path of an ultrasonic wave, the sound pressure level loss for a wave passing between points 1 and 2 is given by

$$SPL_1 - SPL_2 = 20 \cdot \log \frac{P_1}{P_2} \quad dB \qquad \text{(Eq. 2.8)}$$

If the stations are separated by a distance L and the material has an attenuation of α, Eq. 2.8 can be written as

$$\alpha \cdot L = 20 \cdot \log \frac{P_1}{P_2} \quad dB \qquad \text{(Eq. 2.9)}$$

Typically, L would be expressed in units of length (e.g., meters) and α in decibel per meter. A table of attenuation coefficients for various materials would be of doubtful value. Where values have already been reliably measured, which is very difficult below 10 dB/m, such values, in the case of metals, depend within wide limits on the

various manufacturing parameters [4]. Therefore Table 2.2 is to provide a general information for attenuation of longitudinal waves.

Table 2.2: Attenuation of longitudinal waves at 2 MHz and room temperature in various materials [4]

<table>
<tr><td>Attenuation Coefficient α in dB/m</td><td>Low to 10</td><td>Medium 10 to 100</td><td>High above 100</td></tr>
<tr><td rowspan="6">Material</td><td rowspan="6">*Cast:* aluminum, magnesium, pure and slightly alloyed
Worked: steel, aluminum, magnesium, nickel, silver, titanium, tungsten (all pure and alloyed)
Non Metals: glass, porcelain</td><td colspan="2">Predominantly absorption</td></tr>
<tr><td>Plastics (polystyrene, Perspex, rubber, PVC, synthetic resins</td><td>Plastics with fillers, and rubber, vulcanized rubber, wood</td></tr>
<tr><td colspan="2">Predominantly scattering</td></tr>
<tr><td colspan="2">Cast aluminum and magnesium, alloyed</td></tr>
<tr><td>Cast steel, slightly alloyed, high quality cast iron
Worked: copper, zinc, bronze, lead, satellite, sintered metals</td><td>Cast steel, highly alloyed, low strength cast iron, cast copper, zinc, brass, bronze
Non-Metals: porous ceramics, rocks</td></tr>
<tr><td>Max. thickness that can be tested</td><td>1 to 10 m</td><td>0.1 to 1 m</td><td>0 to 0.1 m, can frequently no longer be tested</td></tr>
</table>

As it was seen from the above table the value of the coefficient α varies considerably with the material and state of cold work and/or heat treatment. Experimental data obtained at frequencies typically used for ultrasonic inspection are shown in Table 2.3 for some engineering materials

Table 2.3: Typical attenuation coefficients for engineering materials [3]

Material	Frequency (MHz)	Mode	α (dB/m)
Rail, pearlitic steel	1	long	5,3
Rail, pearlitic steel	2,25	long	5,6
Rail, pearlitic steel	5	long	6,1
Rail, pearlitic steel	2,25	shear	8,8
Hypoeutectoid steel, normalized	2,25	long	70
Stainless steel, 3XX	2,25	long	110
Aluminum, 6061-T6511	2,25	long	90
Plastic (clear acrylic)	2,25	long	380

These data show the frequency dependence of attenuation, as well as the higher value obtained for shear waves as compared to longitudinal waves for the same frequency and material. The significantly higher value for the normalized, hypoeutectoid steel may be explained by the ferrite surrounding the pearlite. Worked steel, as predicted, shows a lower attenuation due to a breakdown of the grain boundaries.

The frequency range used in testing materials, the grain size is usually smaller than the wave length. Under these conditions scatter occurs instead of geometric division, as when the light of a headlamp is scattered by the small water droplets in fog. In the cage of grain sizes of 1/1000th to 1/100th of the wave length, scatter is for all practical purposes negligible. It increases very rapidly, however, approximately as the third power of the grain size, to make itself felt at sizes from l/10th to the full value of the wave length, to such an extent that testing may become impossible if the material concerned is anisotropic. [4]

The second cause of the attenuation, viz. absorption, is a direct conversion of sound energy into heat, for which several processes can be responsible. Absorption can roughly be visualized as a sort of braking effect of the oscillations of the particles, which also makes it clear why a rapid oscillation loses more energy than a slow oscillation; the absorption usually increases as the frequency, i.e. at a rate much slower than the scattering.

Both losses set limitations to the testing of materials, but in slightly different ways. Pure absorption weakens the transmitted energy or the echo from both the flaw and the backwall. To counteract this effect the transmitter voltage and the amplification can be increased or the lower absorption at lower frequencies can be exploited for this purpose. Much more awkward, however, is the scattering because in the echo method, it not only reduces the height of the echo from both the flaw and the backwall but in addition produces numerous echoes with different transit times, the so-called grass in which the true echoes may get lost. The scattering can be compared with the effect of fog in which the driver of an automobile is blinded by his own headlights and is unable to see clearly. Apparently this disturbance cannot be counteracted by stepping up the transmitter voltage or the amplification because the "grass" increases simultaneously. The only remedy is to use lower frequencies,

which due to the reduced beaming effect of the sound and the increasing length of the pulses sets a natural and insuperable limit to the delectability of small flaws.

2.7 Acoustic Impedance

Sound travels through materials under the influence of sound pressure. Because molecules or atoms of a solid are bound elastically to one another, the excess pressure results in a wave propagating through the solid.

The percentages of energy transmitted and reflected depend on the specific acoustic impedance, Z, defined for each material. The acoustic impedance (Z) of a material is defined as the product of density (ρ) and acoustic velocity (V) of that material

$$Z = \rho \cdot V \qquad \text{(Eq. 2.10)}$$

Acoustic impedance is important in

1. The determination of acoustic transmission and reflection at the boundary of two materials having different acoustic impedance
2. The design of ultrasonic transducers.
3. Assessing absorption of sound in a medium.

For two materials of different acoustic impedances, Z_1 and Z_2, percentage of energy transmitted, E_T is given by

$$E_T = \frac{4 \cdot Z_1 \cdot Z_2}{(Z_1 + Z_2)^2} \times 100 \qquad \text{(Eq. 2.11)}$$

and the reflected energy E_R, by

$$E_R = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2 \times 100 \qquad \text{(Eq. 2.12)}$$

These formulates are valid for both compressional and transverse waves, but as a transverse wave cannot be sustained in a liquid, a transverse wave is always completely reflected at a solid/gas interface. [2]

A common practical case is the water/steel (or steel/water) interface. Inserting suitable values, it can be calculated that at a water/steel interface, 12% of the incident energy is reflected and 88% is transmitted. It should be noted that equation 2.11 and 2.12 are for transmitted and reflected *energies;* for amplitude values, the square root is taken. These equations are for single, large-area interfaces, but the double interface is also of practical importance (Fig. 2.5).

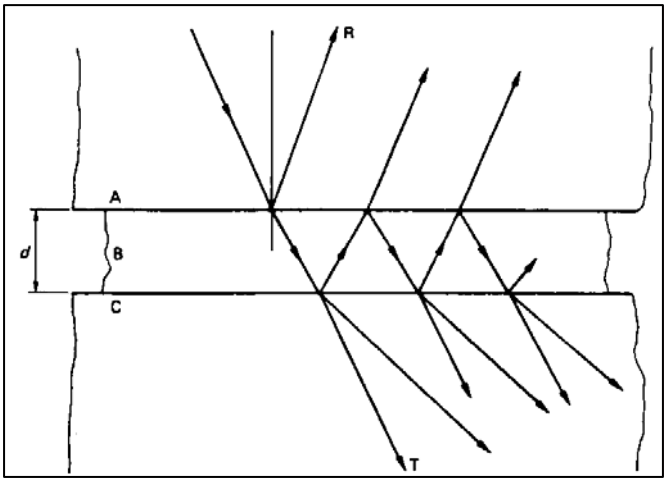


Fig. 2.5 Ultrasonic wave on an interface between two materials, A and C, with a coupling layer, B. Here T denotes transmitted beam and R the reflected beam [2]

The wave in material A is split at the interface between A and B into a transmitted and reflected wave and the transmitted component is again divided at the interface between B and C and so on: the result is a sequence of reflected waves in both directions between A and C, and depending on the wave phases there may be interference in both the reflected and transmitted components. Maximum transmission occurs when the distance *d* is an integral number of half-wavelengths and minimum transmission when *d* is an odd number of quarter-wavelengths. The effect is of importance in determining the thickness of liquid couplant used as an interface between the piezoelectric element of a probe and the specimen surface. For optimum transmission, the couplant should have a thickness of one half-wavelength. [2]

A second special case of the multiple interfaces is an air-filled crack in metal with a very narrow (much less than one wavelength) opening width. Calculated results given by Krautkramer show that with a gap of about 10^{-6} mm in a steel specimen, the calculated theoretical reflection from the crack is about 70%, and larger gaps reflect effectively 100%. Only therefore with extremely tight cracks is there a possibility of partial transmission across an air gap. In practice, because of the irregularities in 'real' crack opening widths and the influence of foreign material on the crack surfaces, apparently : wider cracks can be semi-transparent to ultrasonic energy: nevertheless, unless the crack opening width is less than 1 μm, there should be no practical problem in having sufficient reflected ultrasonic energy for crack detection. [2]

2.8 Refraction and Mode Conversion

When an ultrasonic beam is incident at any angle except the normal at an interface between two media having different acoustic impedances, it can produce both reflected and refracted compressional and shear waves. Fig. 2.6

A simple relationship, known as *Snell's law* describes the angle of refraction of the transmitted wave,

$$\frac{\sin\alpha}{\sin\beta} = \frac{V_A}{V_B} \qquad \text{(Eq. 2.13)}$$

where α and β are the angles of incidence and refraction respectively and V_A and V_B are the wave velocities in the two media A and B.

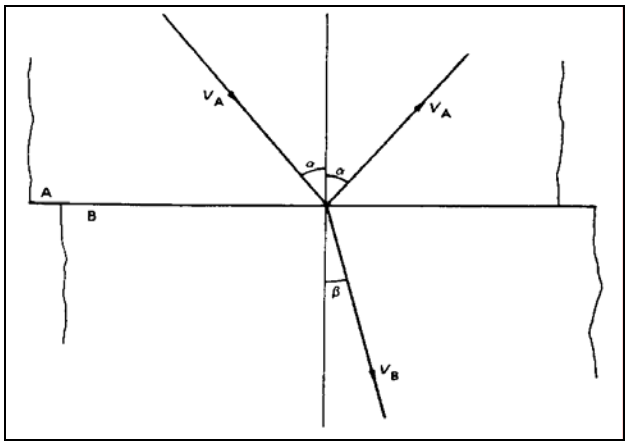


Fig. 2.6 Ultrasonic wave at an angle on an interface between two materials, A and B, in which the waves have different velocities $V_A > V_B$ [2]

For the reflected wave in medium A, the angle of incidence is equal to the angle of reflection. These expressions hold for both incidence compressional and shear waves. When *VB> VA* it is possible to have an angle of incidence α which would make β = 90°. α is then referred to as the *critical angle,* and for angles of incidence greater than this the wave is totally reflected and no energy is transmitted into the second medium. In the case of a water/steel interface, the critical angle for a compressional wave is about 15°. At the interface between two solid media there are two critical angles, one at which the transmitted compressional wave disappears and one beyond which the transmitted shear wave no longer exists. At a Perspex/aluminum interface, such as that in a shear wave probe, these angles are 25.5° and 61.3° respectively. [2]

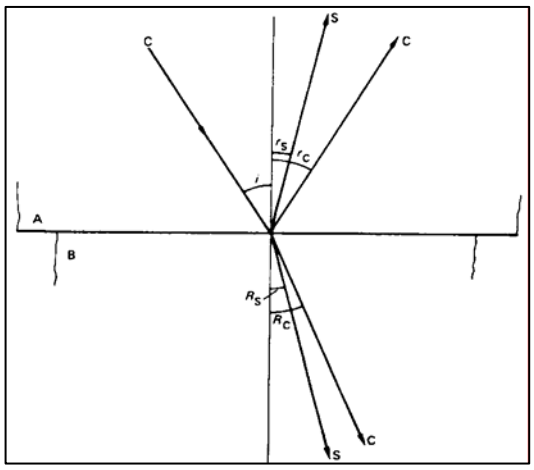


Fig. 2.7 Compressional wave at an angle on to an interference between two materials A,B showing mode conversion. C denotes comp. compressional wave and S shear wave, r_C=i (the angle of incidence) and $V_A > V_B$ [2]

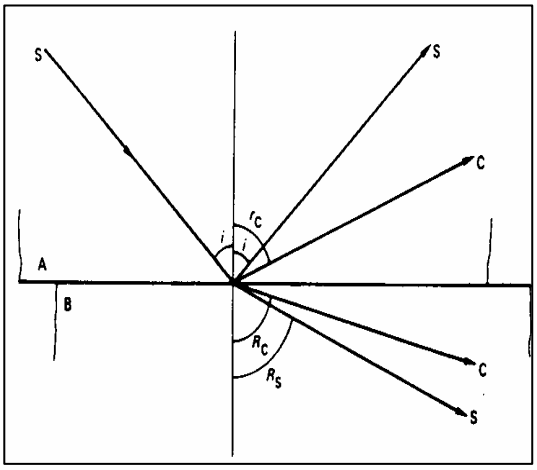


Fig 2.8 Shear wave at an angle on to an interference between two materials A,B. showing mode conversion. C denotes compressional wave (the angle of incidence) and $V_B > V_A$ [2]

At an interface it is possible to have wave mode conversion and Figs 2.7 and 2.8 show the general cases of an incident compressional and shear wave respectively.

In Fig. 2.7

$$\frac{\sin i}{V_{CA}} = \frac{\sin r_S}{V_{SA}} = \frac{\sin r_C}{V_{CA}} = \frac{\sin R_S}{V_{SB}} = \frac{\sin R_C}{V_{CB}} \qquad \text{(Eq. 2.14)}$$

and in Fig. 2.8

$$\frac{\sin i}{V_{SA}} = \frac{\sin r_C}{V_{CA}} = \frac{\sin R_S}{V_{SB}} = \frac{\sin R_C}{V_{CB}} \qquad \text{(Eq. 2.15)}$$

where V_{CA} and V_{SA} are the velocities of the compressional and shear waves respectively in medium A and V_{CB} and V_{SB} are the velocities of the compressional and shear waves respectively in medium B.

In both cases, depending on the incidence angle, some of the secondary waves may not exist.

In practical ultrasonic testing, certain cases are particularly important. The solid/solid case occurs with contact probes on metal surfaces, although usually a thin layer of liquid couplant is used between the solids and this liquid cannot transmit shear waves, so the practical case is solid/liquid/solid. For shear wave inspection, which is widely used in weld inspection, the incident angles of interest are those between the two critical angles and the usual requirement is for a transmitted shear wave at 45°-80°. lf 70° shear wave beam (i.e. 70° to the normal) is required in steel, then the angle of incidence in Perspex of the incident compressional wave can easily be calculated by Snell's law to be 54°. [2]

The water/metal case occurs with stand-off probes and with immersion testing. The efficiency of energy transmission across the interface varies markedly with angle. These show that for incident angles up to 30° it is better to operate with compressional waves, but above 35° shear waves become more favorable. [2]

2.9 Ultrasonic Testing Principles

Ultrasonic nondestructive testing is a versatile technique that can be applied to a wide variety of material analysis applications. While ultrasonic NDT is perhaps better known in its more common applications for thickness gauging, flaw detection, and acoustic imaging, high frequency sound waves can also be used to discriminate and quantify some basic mechanical, structural, or compositional properties of solids and liquids. Ultrasonic material analysis is based on a simple principle of physics: the motion of any wave will be affected by the medium through which it travels. Thus, changes in one or more of four easily measurable parameters associated with the passage of a high frequency sound wave through a material transit time, attenuation, scattering, and frequency content can often be correlated with changes in physical properties such as hardness, roughness, elastic modulus, density, homogeneity, or grain structure.

As it is mentioned before, ultrasonic NDT utilizes the range of frequencies from approximately 20 KHz to over 100 MHz, with most work being performed between 500 KHz and 20 MHz. Both longitudinal and shear (transverse) modes of vibration are commonly employed, as well as surface (Rayleigh) waves and plate (Lamb) waves in some specialized cases. Because shorter wavelengths are more responsive to changes in the medium through which they pass, many material analysis applications will benefit from using the highest frequency that the test piece will support. Sound pulses are normally generated and received by piezoelectric transducers that have been acoustically coupled to the test material. In most cases a single transducer coupled to one side of the test piece serves as both transmitter and receiver (pulse/echo mode), although in some situations involving highly attenuating or scattering materials separate transmitting and receiving transducers on opposite sides of the part are used (through transmission mode). A sound wave is launched by exciting the transducer with either a voltage spike or a continuous wave impulse. The sound wave travels through the test material, either reflecting off the far side to return to its point of origin (pulse/echo), or being received by another transducer at that point (through transmission). The received signal is then amplified and analyzed. A variety of commercial instrumentation is available for this purpose, utilizing both analog and digital signal processing. A significant advantage of ultrasonic testing

over other material analysis methods is that it can often be performed in-process or on-line. High frequency sound waves can often be successfully transmitted into and out of moving materials without direct contact, through the use of a water bath or water stream as a coupling medium. Measurements can also be performed within closed containers by coupling sound energy through the wall. Because sound waves penetrate through the test specimen, material properties are measured in bulk rather than just on the surface. It is sometimes even possible, through the use of selective gating, to analyze just one layer of a multilayer, multi-material fabrication.

The relevant measurement parameters will typically be one or more of the following:

1. Sound velocity/pulse transit time: Sound velocity is usually the easiest ultrasonic parameter to measure. The speed of sound in a homogenous medium is directly related to both elastic modulus and density; thus changes in either elasticity or density will affect pulse transit time through a sample of a given thickness. Additionally, varying degrees of non-homogeneity may have an effect on sound velocity.

2. Attenuation: Sound energy is absorbed or attenuated at different rates in different materials, governed in a complex fashion by interactive effects of density, hardness, contact surface roughness, viscosity and molecular structure. Attenuation normally increases with frequency in a given material.

3. Scattering: Sound waves reflect from boundaries between dissimilar materials. Changes in grain structure, fiber orientation, porosity, particle concentration, and other microstructural variations can affect the amplitude, direction, and frequency content of scattered signals. Scatter effects can also be monitored indirectly by looking at changes in the amplitude of a backwall echo or a through-transmission signal.

4. Frequency (Spectrum) content: All materials tend to act to some degree as a low pass filter, attenuating or scattering the higher frequency components of a broadband sound wave more than the lower frequency components. Thus, analysis of changes in the remaining frequency content of a selected

broadband pulse that has passed through the test material can track the combined effects of attenuation and scattering as described above.

In some applications ultrasonic data such as velocity can be directly used to calculate properties such as elastic modulus. In other cases, ultrasonic testing is a comparative technique, where in order to establish a test protocol in a given application it will be necessary to experimentally evaluate reference standards representing the range of material conditions being quantified. From such standards it will be possible to record how sound transmission parameters vary with changes in specific material properties, and then from this baseline information it will be possible to identify or predict similar changes in test samples.

2.9.1 Applications

The following is a summary of some specific material analysis applications where ultrasonic techniques have been used and documented.

- Elastic modulus: Young's modulus and shear modulus in homogenous, non-dispersive materials can be calculated from longitudinal wave and shear wave velocity (along with material density). Use of waveguides often permits measurement at high temperatures.

- Nodularity in cast iron: Both the concentration of graphite in cast iron and its shape and form can be quantified through velocity measurements.

- Cure rate in epoxies and concrete: The speed of sound in these materials changes as they harden; thus sound velocity measurements can be correlated to the degree of curing. Concrete testing usually requires access to both sides for through-transmission coupling.

- Liquid concentrations: The mixture ratio of two liquids with dissimilar sound velocities can be correlated to the sound velocity of the solution at a given temperature.

- Density of slurries: The liquid/solid mix ratio of slurries such as drilling mud and paper slurry at a given temperature can be correlated to sound velocity and/or attenuation.

- Density in ceramics: Uniformity of density in both green and fired ceramics can be verified by means of sound velocity measurements.

- Food products: A wide variety of tests have been reported, including age of eggs and potatoes, ripeness of fruits, fat content in beef, and percent of solids in milk. Generally these tests are both nondestructive and non-contaminating.

- Polymerization in plastics: In plastics and other polymers, variations in molecular structure such as length or orientation of polymer chains will often result in corresponding changes in sound velocity and/or attenuation.

- Particle or porosity size and distribution: Changes in the size or distribution of particles or porosity in a solid or liquid medium will affect the amplitude and frequency of scattered ultrasound.

- Grain size in metals: Changes in grain size or orientation in steel, cast iron, titanium, and other metals will cause changes in the amplitude, direction, and/or frequency content of scattered ultrasound.

- Anisotropy in solids: Variations in sound velocity, scattering, and/or attenuation across different axes of a solid can be used to identify and quantify anisotropy.

- Case hardening depth in steel: High frequency shear wave backscatter techniques can be used to measure the depth of case hardening.

- Temperature measurement: Ultrasonic thermometry has been used to measure very high temperatures (over 3,000 degrees Celsius) by monitoring changes in sound velocity in a reference medium.

2.9.2 Equipment and Transducers

2.9.2.1 Piezoelectric Transducers

An important feature of any ultrasonic instrumentation system is the transducer. The active element of most acoustic transducers is piezoelectric element, which converts electrical signals into mechanical vibrations (transmit mode) and mechanical vibrations into electrical signals (receive mode), and vice versa. So this means, this piezoelectric element is the heart of the transducer.

Piezoelectric elements were introduced in the early 1950's. Preceding the advent of piezoelectric ceramic, piezoelectric crystals made from quartz and magnetostrictive materials were used in the design of transducers. Due to the high costs to manufacture and limitations in the piezoelectric properties of both these materials they are rarely used in transducers today.

When piezoelectric ceramics were introduced they soon became the dominant material for transducers due to their good piezoelectric properties and their ease of manufacture into a variety of shapes and sizes. The first piezoceramic in general use was barium titanate, and that was followed during the 1960's by lead zirconate titanate compositions, which are now the most commonly employed ceramic for making transducers.

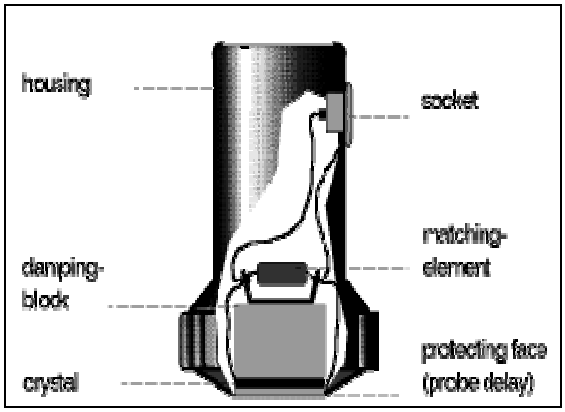


Fig. 2.9 Straight beam probe

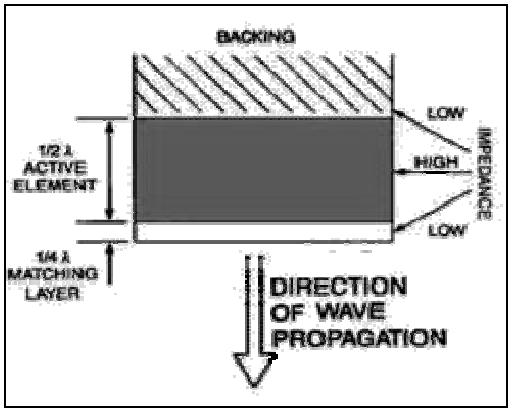


Fig. 2.10 Piezoelectric material in probe*

** A thin wafer vibrates with a wavelength that is twice its thickness; therefore, piezoelectric crystals are cut to a thickness that is 1/2 the desired radiated wavelength. Optimal impedance matching is achieved by a matching layer with thickness 1/4 wavelength. [1]*

In selecting a transducer, the piezoelectric material is always a consideration as; some materials are more efficient transmitters and some are more efficient receivers. Understanding the internal structure of the material to be inspected, as well as type, size, and probable location of defects is helpful when selecting a transducer. A transducer that performs well in one application will not always produce similar results when material properties change. For example, sensitivity to small defects is proportional to the product of the efficiency of the transducer as a transmitter and a receiver. Resolution, the ability to locate defects near surface or in close proximity in the material, requires a highly damped transducer. The backing material supporting the crystal has a great influence on damping characteristics of a transducer. Using a backing material with impedance similar to that of the crystal will produce the most effective damping. Such a transducer will have a narrow bandwidth resulting in higher sensitivity. As the mismatch in impedance between crystal and backing material increases, transducer sensitivity is reduced and material penetration increased.

It is of importance to understand the concept of bandwidth, or range of frequencies, associated with a transducer. The frequency noted on a transducer is the central or center frequency and depends primarily on the backing material. Highly damped transducers will respond to frequencies above and below the central frequency. The broad frequency range provides a transducer with high resolving power. Less damped transducers will exhibit a narrower frequency range, poorer resolving power, but greater penetration. The central frequency will also define capabilities of transducers. Lower frequencies (0.5Mhz-2.25Mhz) provide greater energy and penetration in material, while high frequency crystals (15.0 MHz - 25.0 MHz) provides reduced penetration but greater sensitivity to small discontinuities.

2.9.2.2 Characteristics of Piezoelectric Transducers

The ultrasonic field from such a transducer is often the feature that limits system performance. Many factors, including material, mechanical and electrical construction, and the external mechanical and electrical load conditions, influence the behavior of a transducer. Mechanical construction is the factor that influences performance, with important parameters such as radiation surface area, mechanical

damping, housing, and other variables of physical construction. So, transducer manufactures are hard pressed when constructing two transducers that have identical performance characteristics. Transducer manufacture still has something of a "black art" component.

Transducers are constructed to withstand some abuse, but they should be handled carefully. Misuse such as dropping can cause cracking of the ware plate, element, or the backing material. Damage to a transducer is often noted on the a-scan presentation as an enlargement of the initial pulse. Almost all transducers will have a serial number, element dimensions, and frequency marked on them. Serial numbers are important when tractability of an inspection is required.

Transducers are classified into groups according to the application.

- Contact transducers are used for direct contact inspections, and are manipulated by a technician. Coupling materials of water, grease, oils, or commercial materials are used to smooth rough surfaces and prevent an air gap between the transducer and the component inspected.

- Immersion transducers do not contact the component. These transducers are designed to operate in a liquid environment and all connections are watertight. Fixtures or robotics are often employed when using immersion transducers. Some of these transducers may be operated by the technician. Wheel transducers are examples of such immersion applications.

2.9.2.3 Transducer Beam Spread

Ultrasound intensity along the beam depends on the size and source of diffraction effects. There are extensive fluctuations near the source, known as the near field (near zone) or Fresnel zone. Because of the variations within the near field, it can be extremely difficult to accurately evaluate flaws in materials. The ultrasonic beam is more uniform in the far field, or Fraunhofer zone, where the beam spreads out in a pattern originating from the center of the transducer. [1]

The transition between these zones occurs at a distance, ***N*** and is sometimes referred to as the "natural focus" of a flat (or unfocused) transducer. The near/far distance, ***N*** is significant because amplitude variations that characterize the near field (and can make flaw evaluation difficult) change to smoothly declining amplitude as the distance from the transducer increases.

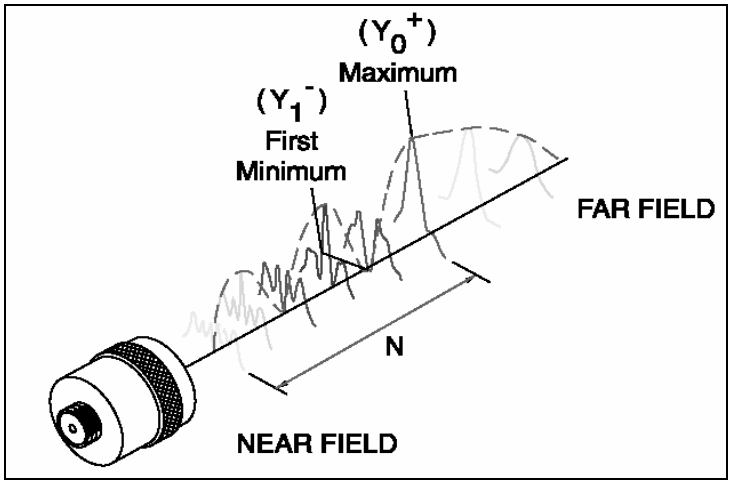


Fig. 2.11 Sound Field

As it is seen from the figure, the near field is the region directly in front of the transducer where the echo amplitude goes through a series of maxima and minima and ends at the last maximum, at distance N from the transducer.

The location of the last maximum is known as the near field distance (N or Y+0) and is the natural focus of the transducer. The far field is the area beyond N where the sound field pressure gradually drops to zero. Because of the variations within the near field it can be difficult to accurately evaluate flaws using amplitude based techniques. The near field distance is a function of the transducer frequency, element diameter, and the sound velocity of the test material and can be evaluated as

$$N = \frac{D^2}{4 \cdot \lambda} \qquad \text{(Eq. 2.16)} \qquad \text{or} \qquad N = \frac{D^2 \cdot f}{4 \cdot c} \qquad \text{(Eq. 2.16a)}$$

where *N= Near Field Distance(mm), f= Frequency(Hz), λ=Wavelength (mm), c=Material Sound Velocity(m/s), D= Element Diameter (mm), D_{eff} = Transducer effective Diameter (mm), D_B = Beam Diameter (mm), ν = Angle of Divergence*

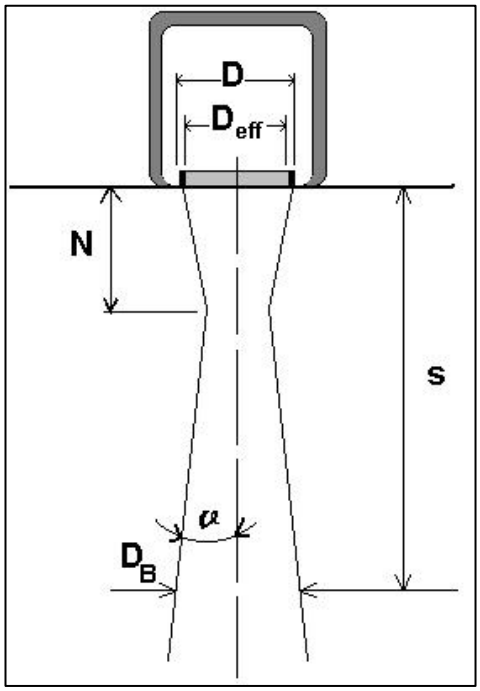


Fig. 2.12 Transducer beam spread

$$D_{eff} \approx 0.95 \cdot D \qquad \text{(Eq. 2.17)}$$

$$[D_B]_{-6dB} = \frac{\lambda \cdot s}{D} \qquad \text{(Eq. 2.18)}$$

$$[D_B]_{-20dB} = \frac{2 \cdot \lambda \cdot s}{D} \qquad \text{(Eq. 2.19)}$$

$$[\sin \nu]_{-6dB} = 0{,}5\frac{\lambda}{D} \qquad \text{(Eq. 2.20)}$$

$$[\sin \nu]_{-20dB} = 0{,}5\frac{\lambda}{D} \qquad \text{(Eq. 2.21)}$$

2.9.2.4 Pulser & Receivers

Ultrasonic pulser-receivers are well suited to general purpose ultrasonic testing. Along with appropriate transducers and an oscilloscope they can be used for flaw detection and thickness gauging in a wide variety of metals, plastics, ceramics, and composites. Ultrasonic pulser-receivers provide a unique, low-cost ultrasonic measurement capability.

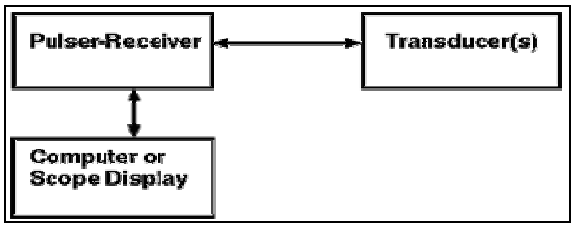


Fig. 2.13 Pulser & Receiver in system

The pulser section of the instrument generates short, large amplitude electric pulses of controlled energy which, when applied to an ultrasonic transducer, are converted into short ultrasonic pulses. Most pulser sections have very low impedance outputs to better drive transducers. Control function associated with the pulser circuit include

- Pulse length or damping (The amount of time that the pulse is applied to the transducer.)
- Pulse energy (The voltage applied to the transducer. Typical pulser circuits will apply from 100 volts to 800 volts to a transducer.)

In the receiver section the voltage signals produced by the transducer, which represents the received ultrasonic pulses, are amplified. The amplified radio frequency (RF) signal is available as output for display or capture for signal processing. Control functions associated with the receiver circuit include

- Signal rectification (The RF signal can be viewed as positive half wave, negative half wave or full wave.)
- Filtering to shape and smooth return signals
- Gain, or signal amplification
- Reject control

The pulser-receiver can be used in material characterization work measuring sound velocity or attenuation, which in turn can be correlated to such material properties as elastic modulus or grain orientation. In conjunction with a stepless gate and a spectrum analyzer, the pulser-receiver can also be used to study frequency dependent material properties or to characterize the performance of ultrasonic transducers.[1]

2.10 Pulse echo system

A part from some older types of ultrasonic thickness gauge which used continuous waves with resonance technique, and a few special techniques which measure the transmitted intensity, all other industrial ultrasonic flaw detection methods use the pulse echo system. In this method, which was first proposed by Firestone in 1940, and Sokolov in 1941, and demonstrated by Firestone (1945) and Sproule *et al.* (1945), the principle is as follows. [2]

An electrical pulse is applied to the transmitter probe, which produces a short ultrasonic pulse which is propagated into the specimen through a couplant layer (Fig. 2.14). The same pulse triggers a time base generator, so that the pulse of ultrasound

starts to move through the specimen at the same time as a spot starts to move across the cathode ray tube, CRT, display screen.

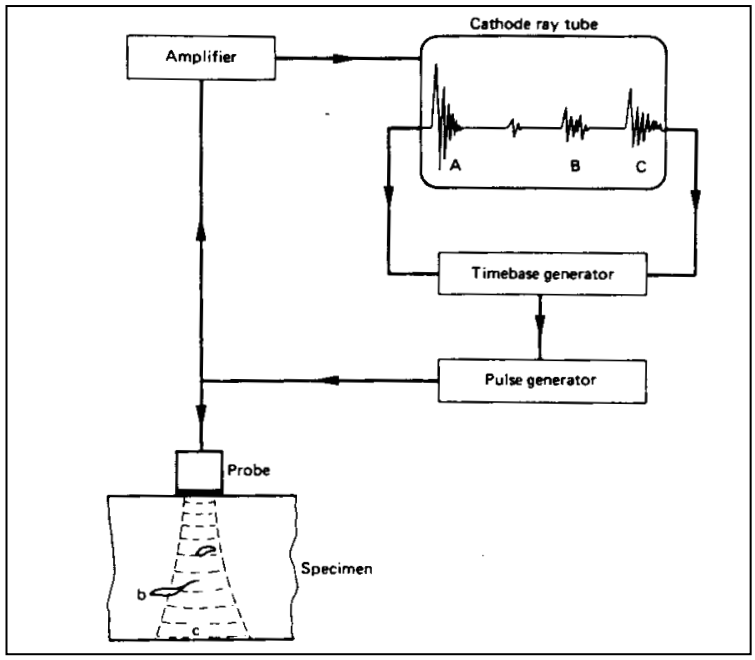


Fig. 2.14 Principles of operation of conventional ultrasonic equipment

Variations in voltage at the transducer due to the ultrasound wave are passed to the amplifier and applied to the Y-axis of the CRT to produce a transmission signal (A), which represents the shape of the generated ultrasonic pulse. The spot continues to move across the screen of the CRT as the sound pulse travels through the specimen until the ultrasonic pulse reaches a reflecting or scattering surface (b). The reflected portion of the ultrasound returns to the transducer, which vibrates, causing a small alternating voltage which is fed to the amplifier, where after amplification it is fed to the Y-plates of the CRT and produces signal *(B),* the echo pulse from the flaw. Further ultrasonic energy in the transmitted pulse may continue to the bottom surface of the specimen plate and be reflected back to the transducer, producing indication (C) on the CRT display, the bottom surface echo.

If the specimen is 100 mm thick, the travel-distance of the ultrasonic pulse would be 200 mm, which in steel will take only 33 μs: obviously, the display would be present on the CRT screen for such a short time that it would not be seen. To get an apparently steady display, the process needs to be repeated many times per second-

typically, a pulse-repetition frequency, *PRF,* of 500-2000 pulses per second (pps) is used. At a *PRF* of 1000 pps, the time-gap between pulses is about 1000 μs, so that each pulse has plenty time to reach a distant reflector and to be reflected back to the transducer, before the next pulse is emitted. At the end of each sweep, the CRT spot flies back to the left-hand edge and waits for the next pulse. This timebase scale across the CRT screen is adjusted to correspond with the thickness of the specimen being examined. If the specimen is much thicker, say 1000 mm, then the spot would travel across the CRT screen much more slowly, making a brighter trace and a *PRF* as high as 1000 pps would not be necessary. In fact, if too high a *PRF* was used, the subsequent pulse would be generated before the first returning pulse from the backwall of the specimen has returned, which would produce a very confusing display. Therefore a range of PRF-values is needed, and usual1y this is changed automatically as the depth control on the equipment is set. Modern flaw detectors can display the specimen thickness as a full-scale width on the X-axis of the CRT from about 10 mm steel to 5 m steel, by varying the spot sweep-time from about 4 to 2000 μs. [2]

For probes in which the piezoelectric element is not in contact with the specimen surface, such as the twin crystal probe or immersion probes, it is convenient to display the ultrasonic pulses starting at the specimen surface rather than at the crystal, and a delay control on the timebase generator is used for this, starting the timebase alter a preset delay. This same delay control al1ows the operator to look at part of a thick specimen on an expanded scale on the display. For example, any 20 mm out of a total specimen thickness of 200 mm can be displayed as full-scale width. [2]

Since the ultrasonic signals may be weak or strong, the amplifier needs to have a calibrated gain control. For testing metals, ultrasonic probe frequencies from about 1 to 10 MHz are used, and much equipment is designed to use a slightly wider range of frequencies, from 250 kHz to 20 MHz. The gain control should be calibrated in decibels so that any signal can be increased or decreased in display amplitude by a known amount.

2.10.1 Data Presentation of Ultrasonic Testing

Ultrasonic data can be collected and displayed in a number of different formats. The three most common formats are know in the NDT world as **A-scan**, **B-scan** and **C-scan** presentations. Each presentation mode provides a different way of looking at and evaluating the region of material being inspected. Modern computerized ultrasonic scanning systems can display data in all three presentation forms simultaneously. [1]

A-Scan Presentation

The A-scan presentation displays the amount of received ultrasonic energy as a function of time. The relative amount of received energy is plotted along the vertical axis and elapsed time (which may be related to the sound energy travel time within the material) is display along the horizontal axis. Most instruments with an A-scan display allow the signal to be displayed in its natural radio frequency form (rf), as a fully rectified rf signal, or as either the positive or negative half of the rf signal. In the A-scan presentation, relative discontinuity size can be estimated by comparing the signal amplitude obtained from an unknown reflector to that from a known reflector. Reflector depth can be determined by the position of the signal on the horizontal sweep.

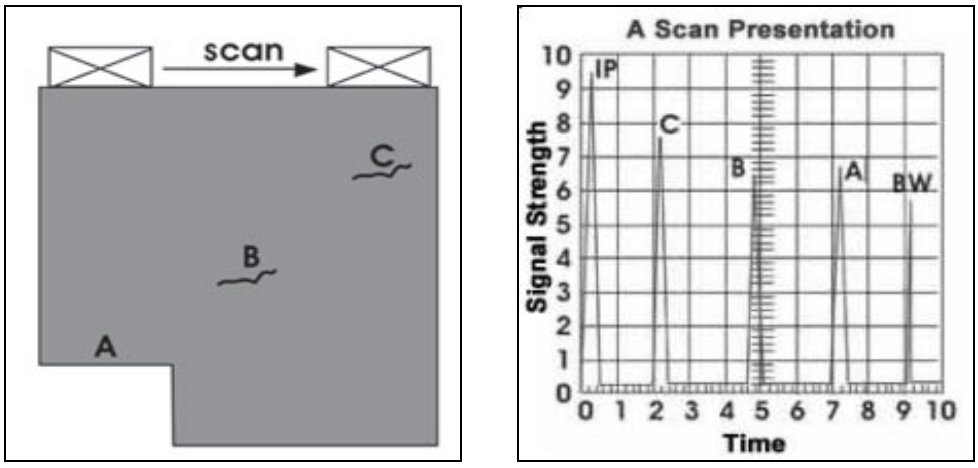


Fig. 2.15 A Typical A-Scan Presentation

In the illustration of the A-scan presentation, the initial pulse generated by the transducer is represented by the signal ***IP,*** which is near time zero. As the transducer

is scanned along the surface of the part, four other signals are likely to appear at different times on the screen. When the transducer is in its far left position, only the ***IP*** signal and signal ***A***, the sound energy reflecting from surface ***A,*** will be seen on the trace. As the transducer is scanned to the right, a signal from the backwall ***BW*** will appear latter in time showing that the sound has traveled farther to reach this surface. When the transducer is over flaw ***B***, signal ***B***, will appear at a point on the time scale that is approximately halfway between the ***IP*** signal and the ***BW*** signal. Since the ***IP*** signal corresponds to the front surface of the material, this indicates that flaw ***B*** is about halfway between the front and back surfaces of the sample. When the transducer is moved over flaw ***C,*** signal ***C*** will appear earlier in time since the sound travel path is shorter and signal ***B*** will disappear since sound will no longer be reflecting from it.

B-Scan Presentation

The B-scan presentation is a profile (cross-sectional) view of the test specimen. In the B-scan, the time-of-flight (travel time) of the sound energy is displayed along the vertical and the linear position of the transducer is displayed along the horizontal axis. From the B-scan, the depth of the reflector and its approximate linear dimensions in the scan direction can be determined. The B-scan is typically produced by establishing a trigger gate on the A-scan. Whenever the signal intensity is great enough to trigger the gate, a point is produced on the B-scan. The gate is triggered by the sound reflecting from the backwall of the specimen and by smaller reflectors within the material.

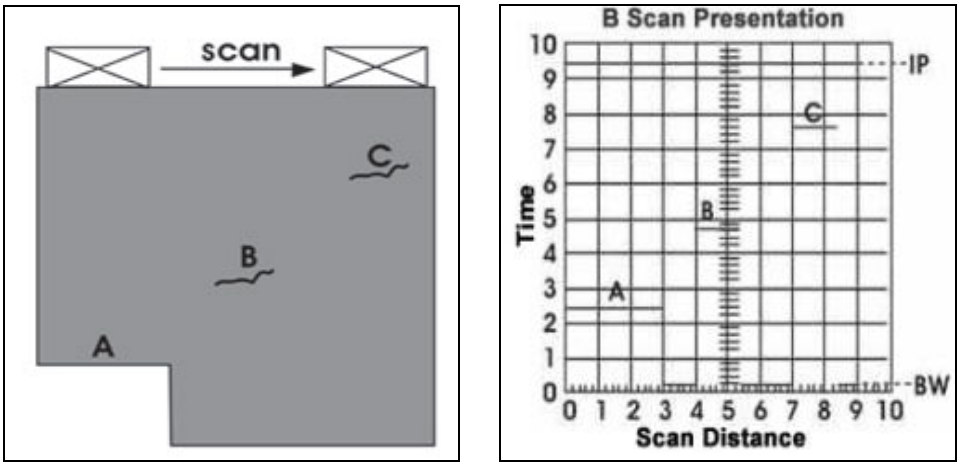


Fig. 2.16 A Typical B-Scan Presentation

In the B-scan image, line ***A*** is produced as the transducer scans over the reduced thickness portion of the specimen. When the transducer moves to the right of this section, the backwall line ***BW*** is produced. When the transducer is over the flaw ***B*** and ***C,*** lines that are similar to the length of the flaws and at similar depths within the material are drawn on the B-scan. It should be noted that a limitation to this display technique is that reflectors may be masked by larger reflectors near the surface.

C-Scan Presentation

The C-scan presentation provides a plan-type view of the location and size of test specimen features. The plane of the image is parallel to the scan pattern of the transducer. C-scan presentations are produced with an automated data acquisition system, such as a computer controlled immersion scanning system. Typically, a data collection gate is established on the A-scan and the amplitude or the time-of-flight of the signal is recorded at regular intervals as the transducer is scanned over the test piece. The relative signal amplitude or the time-of-flight is displayed as a shade of gray or a color for each of the positions where data was recorded. The C-scan presentation provides an image of the features that reflect and scatter the sound within and on the surfaces of the test piece. High resolution scan can be produced by C-Scan.

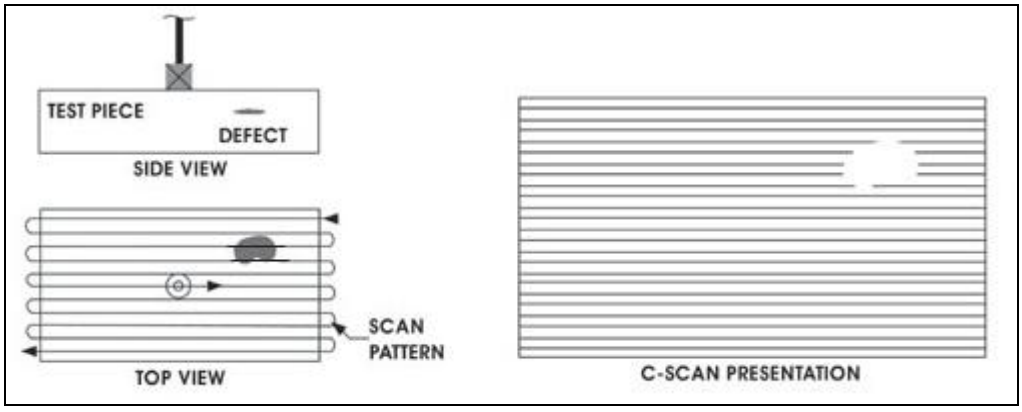


Fig. 2.17 A Typical C-Scan Presentation

2.10.2 Calibration of the Instrument

Calibration refers to the act of evaluating and adjusting the precision and accuracy of measurement equipment. In ultrasonic testing, several forms of calibration must occur. First, the electronics of the equipment must be calibrated to assure that they

are performing as designed. This operation is usually performed by the equipment manufacturer and it is also usually necessary for the operator to perform a "user calibration" of the equipment. This user calibration is necessary because most ultrasonic equipment can be reconfigured for use in a large variety of applications. The user must "calibrate" the system, which includes the equipment settings, the transducer, and the test setup, to validate that the desired level of precision and accuracy are achieved.

In ultrasonic testing, there is also a need for reference standards. Reference standards are used to establish a general level of consistency in measurements and to help interpret and quantify the information contained in the received signal. Reference standards are used to validate that the equipment and the setup provide similar results from one day to the next and that similar results are produced by different systems. Reference standards also help the inspector to estimate the size of flaws. In a pulse-echo type setup, signal strength depends on both the size of the flaw and the distance between the flaw and the transducer. The inspector can use a reference standard with an artificially induced flaw of known size and at approximately the same distance away for the transducer to produce a signal. By comparing the signal from the reference standard to that received from the actual flaw, the inspector can estimate the flaw size.

Calibration and reference standards for ultrasonic testing come in many shapes and sizes. The type of standard used is dependent on the NDE application and the form and shape of the object being evaluated. The material of the reference standard should be the same as the material being inspected and the artificially induced flaw should closely resemble that of the actual flaw. This second requirement is a major limitation of most standard reference samples. Most use drilled holes and notches that do not closely represent real flaws. In most cases the artificially induced defects in reference standards are better reflectors of sound energy (due to their flatter and smoother surfaces) and produce indications that are larger than those that a similar sized flaw would produce. Producing more "realistic" defects is cost prohibitive in most cases and, therefore, the inspector can only make an estimate of the flaw size. Computer programs that allow the inspector to create computer simulated models of the part and flaw may one day lessen this limitation.

CHAPTER 3

SURFACE ROUGHNESS

3.1 Definition of Surface Roughness

It is clear that materials have natural properties such as density, conductivity and elastic modulus. Surfaces, representing material boundaries have perhaps rather more insubstantial properties but we still think of some of these properties are natural, like color. There are other properties, however, which are easy to define but whose value seems to depend on the technique or scale of measurement: hardness, for instance. Roughness seems to be such a property, with the added difficulty that is not always so easy to define as a concept.

The fact is that roughness is the natural state of surfaces, and left to its own devices, nature will make sure they are rough. The roughness of a surface is a measure of its lack of order. Disorder is entropy under another name, and if a solid surface is considered as a closed system then the Second Law of Thermodynamics predicts that its entropy will tend to a maximum. To reduce its roughness, its entropy must be reduced, and the Second Law tells that it can only be done this by doing work. Thus if the axes of the well-known figure are transposed which relates machining time to roughness, it can easily seen that, it is nothing but an entropy diagram. [5] Fig. 3.1

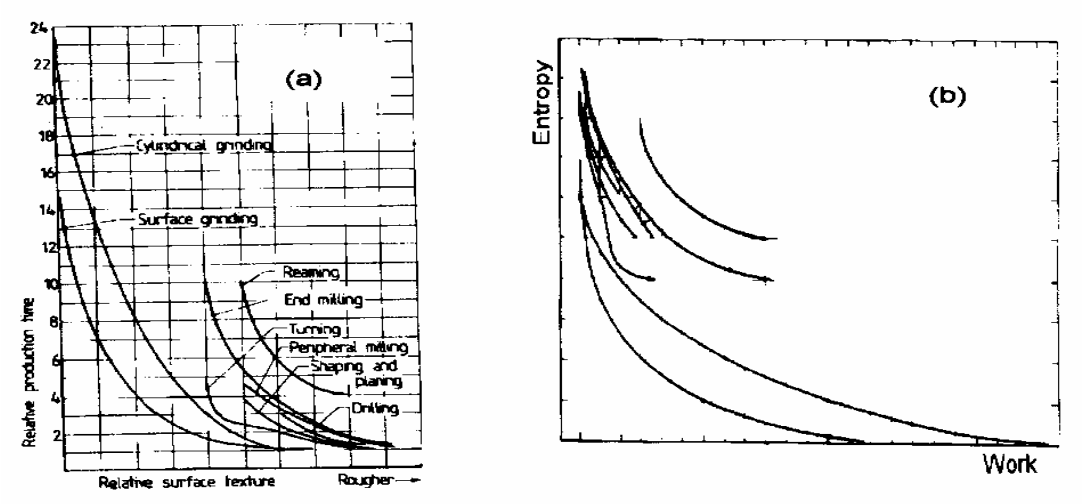


Fig 3.1 Relationship of surface texture to production time (b) the same figure replotted as work reducing entropy [5]

3.2 Subjective and Qualitative Descriptions

By a subjective description we mean one that involves the feelings or impressions of a person. For example, if one tells-a machinist to put a rough turned surface on a piece he will obtain a finish that depends on what the term "rough turned" implies to that machinist. Surfaces can be described or specified by such terms as finely turned, rough ground, finely polished, but they all have the disadvantage of meaning different things to different people, and even the same individual can unconsciously change his ideas about the meaning of these terms. To avoid these uncertainties, standard samples can be prepared and numbered. The finish of a piece can then be described by saying it has the same appearance as the standard of such and such a number. But even then, the opinions of different individuals can vary in making the comparison. To remove as far as possible such variations in opinion as may result from different ways of viewing the surface by different observers, recourse can be had to special devices to aid observation. The inadequacy of methods of describing surfaces which involve personal feelings and non-quantitative concepts has led to attempts to quantitatively describe the roughness of surfaces, using one or more parameters.

3.3 Terminology on Surfaces and Profiles

Types of Surfaces

Surface: A surface is a boundary that separates an object from another object or substance.

Nominal Surface: A nominal surface is the intended surface. The shape and extent of a nominal surface are usually shown and dimensioned on a drawing. The nominal surface does not include intended surface roughness.

Real Surface: A real surface is the actual boundary of an object. It deviates from the nominal surface as a result of the process that created the surface. The deviation also depends on the properties, composition, and structure of the material the object is made of.

Measured Surface: A measured surface is a representation of the real surface obtained with some measuring instrument. This distinction is made because no measurement will give the exact real surface. Later portions describe many different types of measuring instruments.

Form: Form refers to the intentional shape of a surface which differs from a flat line.

Surface Finish Imperfections

Form Error: Form error encompasses the long wavelength deviations of a surface from the corresponding nominal surface. Form errors result from large scale problems in the manufacturing process such as errors in machine tool ways, guides, or spindles, insecure clamping, inaccurate alignment of a work piece, or uneven wear in machining equipment. Form error is on the dividing line in size scale between geometric errors and finish errors.

Texture: Surface texture is the combination of fairly short wavelength deviations of a surface from the nominal surface. Texture includes roughness, waviness, and lay, that is, all of the deviations that are shorter in wavelength than form error deviations.

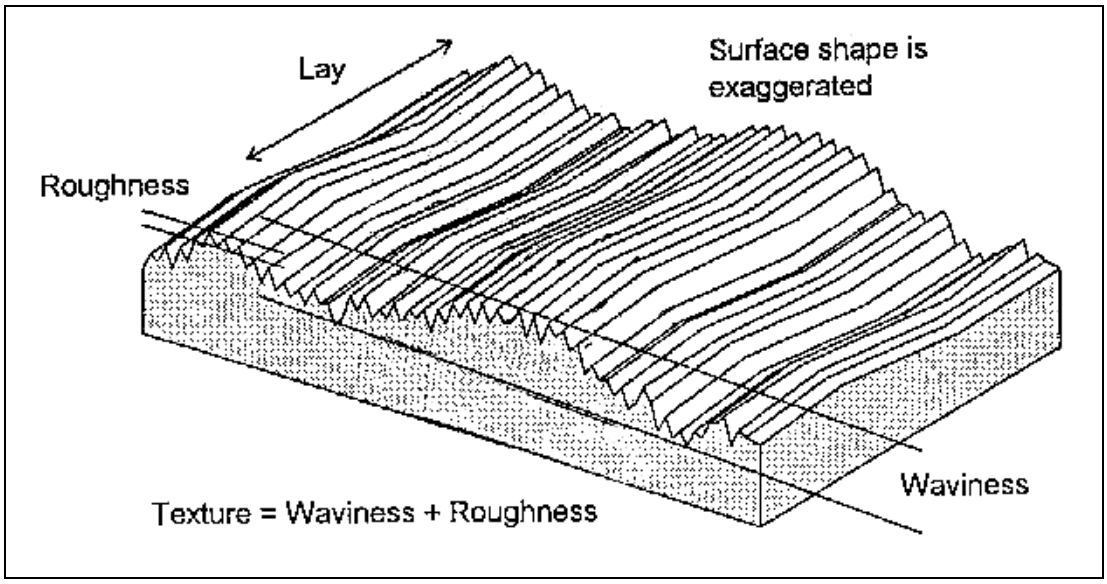


Fig. 3.2 An Exaggerated Surface Shape [6]

Roughness: Roughness includes the finest (shortest wavelength) irregularities of a surface. Roughness generally results from a particular production process or material condition.

Waviness: Waviness includes the more widely spaced (longer wavelength) deviations of a surface from its nominal shape. Waviness errors are intermediate in wavelength between roughness and form error. The distinction between waviness and form error is not always made in practice, and it is not always clear how to make it. New standards are emerging that define this distinction more rigorously. [6]

Lay: Lay refers to the predominant direction of the surface texture. Ordinarily lay is determined by the particular production method and geometry used. Turning, milling, drilling, grinding, and other cutting tool machining processes usually produce a surface that has lay: striations or peaks and valleys in the direction that the tool was drawn across the surface. The shape of the lay can take one of several forms as shown below. Other processes produce surfaces with no characteristic direction: sand casting, spark erosion and grit blasting. Sometimes these surfaces are said to have a non-directional, particulate, or protuberant lay. Several different types of lay are possible depending on the manufacturing and machining processes.

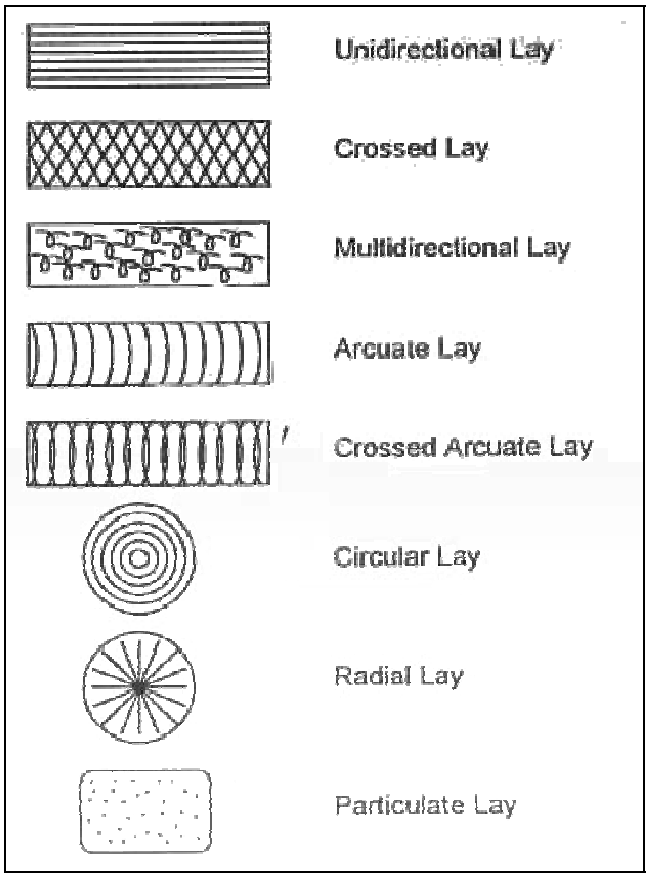


Fig.3.3 Different Types of Lays [6]

Lay (or the lack thereof) is important for optical properties of a surface. A smooth finish will look rough if it has a strong lay. A rougher surface will look more uniform if it has no lay (it will have more of a matte look).

Surface Profiles

Types of Profiles

Profile: A profile is, mathematically, the line of intersection of a surface with a sectioning plane which is (ordinarily) perpendicular to the surface. It is a two-dimensional slice of the three-dimensional surface. Almost always profiles are measured across the surface in a direction perpendicular to the lay of the surface.

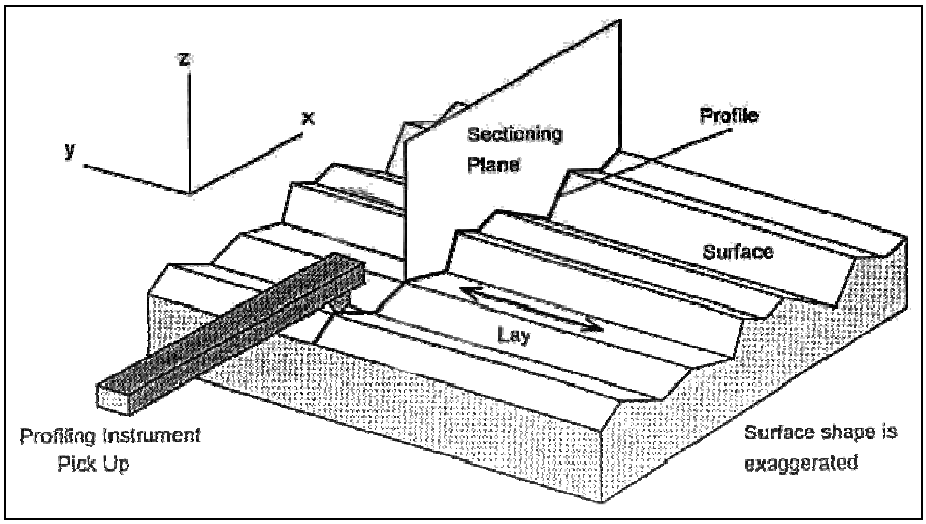


Fig. 3.4 Profile of a Surface [6]

Nominal Profile: The nominal profile is the straight or smoothly curved line of intersection of the nominal surface with a plane which is (ordinarily) perpendicular to the surface. The nominal profile has a known mathematical shape for a known part (most often a straight line or a circle).

Real Profile: A real profile is a profile of the real surface. It is the (idealized) shape of the intersection of a surface with a perpendicular sectioning plane.

Measured Profile: A measured profile is a representation of the real profile obtained with some measuring instrument. This distinction between "real" and "measured" is made because no measurement will give the exact real surface. At the later portions, many different types of measuring instruments, emphasizing profiling instruments are described.

Modified Profile: A modified profile is a measured profile that has been modified by mechanical, electrical, optical, or digital filtering. The filtering is ordinarily done to minimize certain surface characteristics while emphasizing others. A modified profile differs from a measured profile in the sense that the real profile is intentionally modified as part of the measurement. The details of the modification are typically selectable by the user of an instrument. A measured profile is an unintentional modification of the real profile resulting from the limitations of the measuring instrument.

Profiling Methods: A profiling method is a means of measuring a profile of a surface. The result of the method is a two-dimensional graph of the shape of the surface in the sectioning plane created by the profiling instrument.

The most common type of profiling instrument draws a diamond stylus across the surface and measures its vertical displacement as a function of position.

Wavelength: Wavelength is the distance between similar points of a repeating, periodic signal. A real profile can be thought of as the sum of many different individual functions, each with its own wavelength.

Filter: A filter (for purposes of surface finish measurement) is an electronic, mechanical, optical, or mathematical transformation of a profile to attenuate (remove) wavelength components of the surface outside the range of interest for a measurement.

Waviness Profile: The waviness profile includes medium wavelength deviations of the measured profile from the nominal profile. The waviness is the modified profile obtained by filtering a measured profile to attenuate the longest and shortest wavelength components of the measured profile (i.e. the filter removes form error and roughness).

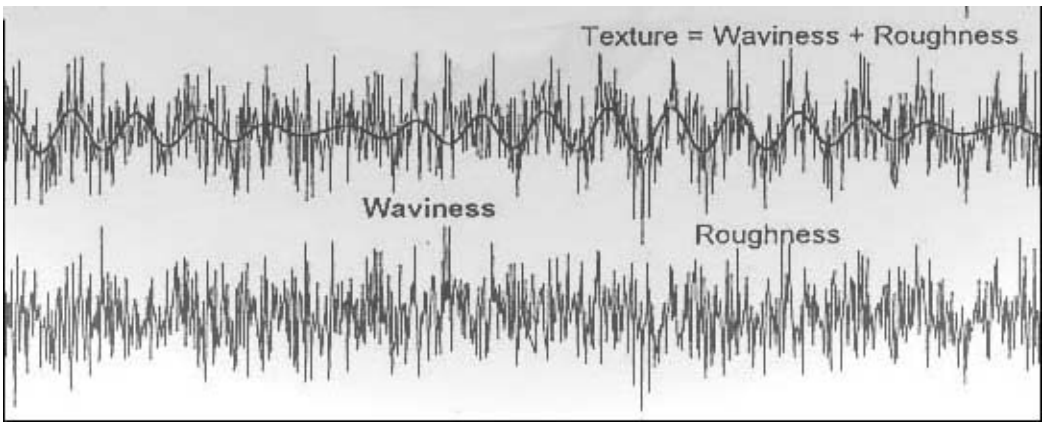


Fig 3.5 Waviness and Roughness [6]

Texture Profile: The texture profile is the sum of the waviness profile and the roughness profile, i.e. the remaining medium and short wavelength deviations of the measured profile from the nominal profile after form error has been subtracted from

the primary profile. Measurement of texture is the primary domain of traditional surface finish analysis.

Roughness Profile: The roughness profile includes only the shortest wavelength deviations of the measured profile from the nominal profile. The roughness profile is the modified profile obtained by filtering a measured profile to attenuate the longer wavelengths associated with waviness and form error. Optionally, the roughness may also exclude (by filtering) the very shortest wavelengths of the measured profile which are considered noise or features smaller than those of interest.

Roughness is of significant interest in manufacturing because it is the roughness of a surface (given reasonable waviness and form error) that determines its friction in contact with another surface. The roughness of a surface defines how that surfaces feels, how it looks, how it behaves in a contact with another surface, and how it behaves for coating or sealing. For moving parts the roughness determines how the surface will wear, how well it will retain lubricant, and how well it will hold a load.

3.4 Surface Profile Parameters

3.4.1 Roughness Amplitude Parameters

Average Roughness - R_a

It is also known as Arithmetic Average (AA), Center Line Average (CLA) and Arithmetical Mean Deviation of the Profile. The average roughness is the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length:

$$R_a = \frac{1}{L}\int_0^L \left|r(x)\right| \cdot dx \qquad \text{(Eqn. 3.1)}$$

When evaluated from digital data, the integral is normally approximated by;

$$R_a = \frac{1}{N}\sum_{n=1}^{N} \left|r_n\right| \qquad \text{(Eqn. 3.2)}$$

Graphically, the average roughness is the area (shown below) between the roughness profile and its center line divided by the evaluation length (normally five sample lengths with each sample length equal to one cutoff):

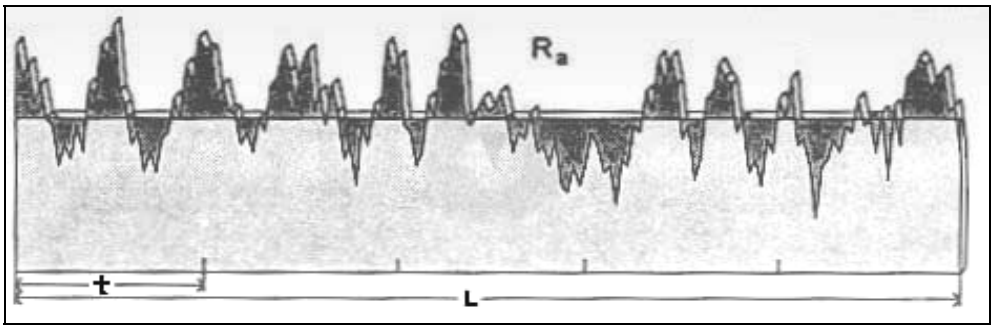


Fig. 3.6 Average Roughness, Ra [6]

The average roughness is by far the most commonly used parameter in surface finish measurement. The earliest analog roughness measuring instruments measured only R_a by drawing a stylus continuously back and forth over a surface and integrating (finding the average) electronically. It is fairly easy to take the absolute value of a signal and to integrate a signal using only analog electronics. That is the main reason R_a has such a long history. [6]

But R_a is not the whole story of roughness. For example, in Fig 3.7 there are three surfaces that all have the same R_a, but no more than eyes are needed to know that they are quite different surfaces. In some applications they will perform very differently as well.

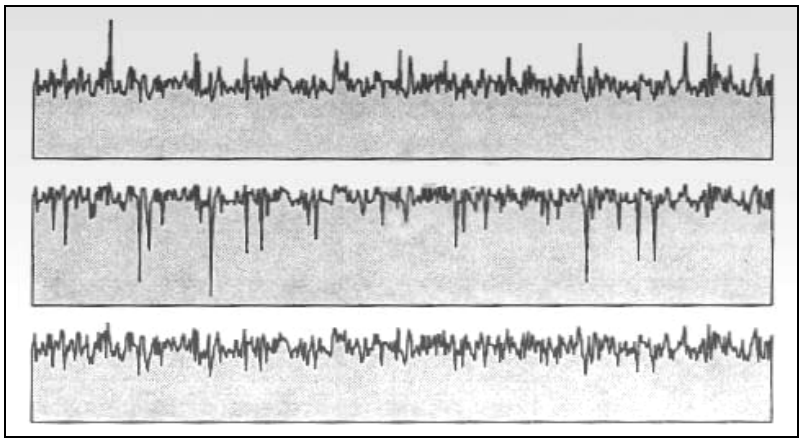


Fig. 3.7 Different Surfaces Having the Same Ra Value [6]

These three surfaces differ in the shape of the profile - the first has sharp peaks, the second deep valleys, and the third has neither. Even if two profiles have similar shapes, they may have a different spacing between features. The following three surfaces also all have the same R_a.

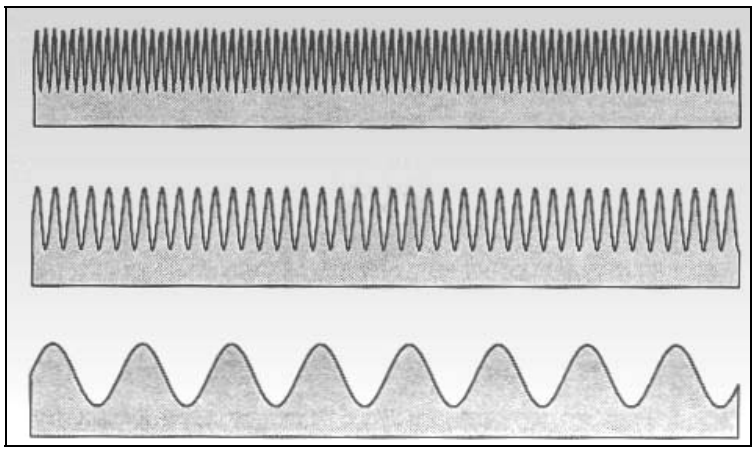


Fig. 3.8 Different Surfaces Having Same R_a Value [6]

If it is wanted to distinguish between surfaces that differ in shape or spacing, calculating other parameters are needed for a surface that measure peaks and valleys and profile shape and spacing. The more complicated the shape of the surface wanted and the more critical the function of the surface, the more sophisticated is needed to be in measuring parameters beyond R_a.

Root-Mean-Square Roughness - R_q

The root-mean-square (rms) average roughness of a surface is calculated from another integral of the roughness profile:

$$R_q = \sqrt{\frac{1}{L}\int_0^L r^2(x)\cdot dx} \qquad \text{(Eqn. 3.3)}$$

The digital equivalent normally used is:

$$R_q = \sqrt{\frac{1}{N}\sum_{n=1}^{N} r_n^2} \qquad \text{(Eqn. 3.4)}$$

For a pure sine wave of any wavelength and amplitude R_q is proportional to R_a; it's about 1.11 times larger. Older instruments made use of this approximation by calculating R_q with analog electronics (which is easier than calculating with analog electronics) and then multiplying by 1.11 to report R_q. However, real profiles are not simple sine waves, and the approximation often fails miserably. Modern instruments either digitize the profile or do not report R_q. There is never any reason to make the approximation that is proportional to R_a. R_q has now been almost completely superseded by Ra in metal machining specifications. But R_q still has value in optical applications where it is more directly related to the optical quality of a surface. [6]

R_t, R_p, and R_v

The peak roughness R_p is the height of the highest peak in the roughness profile over the evaluation length (p1 below). Similarly, R_v is the depth of the deepest valley in the roughness profile over the evaluation length (v1). The total roughness, R_t, is the sum of these two, or the vertical distance from the deepest valley to the highest peak.

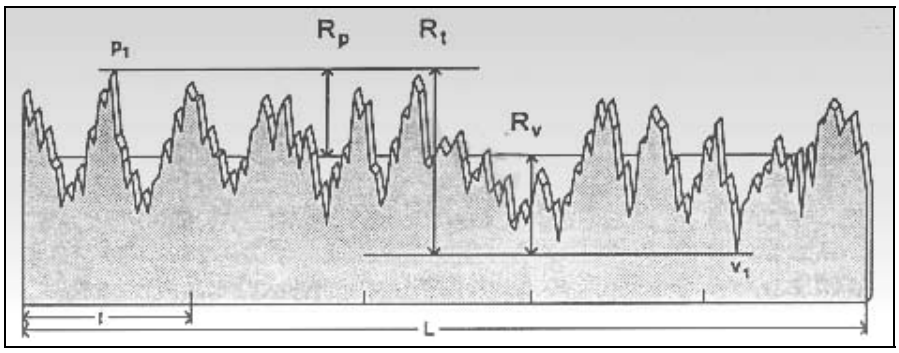


Fig. 3.9 Rt, Rp and Rv

$$R_p = \left|\max\left[r(x)\right]\right|, \qquad 0 < x < L \qquad \text{(Eqn. 3.5)}$$

$$R_v = \left|\min\left[r(x)\right]\right|, \qquad 0 < x < L \qquad \text{(Eqn. 3.6)}$$

$$R_t = R_p + R_v \qquad \text{(Eqn. 3.7)}$$

These three extreme parameters will succeed in finding unusual conditions: a sharp spike or burr on the surface that would be detrimental to a seal for example, or a crack or scratch that might be indicative of poor material or poor processing. [6]

R_{tm}, R_{pm} and R_{vm}

These three parameters are mean parameters, meaning they are averages of the sample lengths. For example, define the maximum height for the i-th sample length as R_{pi}. Then R_{pm} is:

$$R_{pm} = \frac{1}{M}\sum_{i=1}^{M} R_{pi} \qquad \text{(Eqn. 3.8)}$$

Similarly,

$$R_{vm} = \frac{1}{M}\sum_{i=1}^{M} R_{vi} \qquad \text{(Eqn. 3.9)}$$

and

$$R_{tm} = \frac{1}{M}\sum_{i=1}^{M} R_{ti} = R_{pm} + R_{vm} \qquad \text{(Eqn. 3.10)}$$

where R_{vi} is the depth of the deepest valley in the i-th sample length and R_{ti} is the sum of R_{vi} and R_{pi}:

$$R_{pi} = \left|\max\left[r(x)\right]\right|, \qquad i \cdot l < x < (i+1) \cdot l \qquad \text{(Eqn. 3.11)}$$

$$R_{vi} = \left|\min\left[r(x)\right]\right|, \qquad i \cdot l < x < (i+1) \cdot l \qquad \text{(Eqn. 3.12)}$$

$$R_{ti} = R_{pi} + R_{vi} \qquad \text{(Eqn. 3.13)}$$

These three parameters have some of the same advantages as R_t, R_p, and R_v for finding extremes in the roughness, but they are not so sensitive to single unusual features. [6]

R_{ymax} (or R_{max}) - Maximum Roughness Height within a Sample Length

R_y and R_{max} are other names for R_{ti}. R_{max} is the older American name. R_y is the newer ISO and American name. For a standard five cutoff trace, there are five different values of R_y. R_y is the maximum peak to lowest valley vertical distance within a single sample length.

R_z(DIN)

R_z(DIN), i.e. R_z according to the German DIN standard, is just another name for R_{tm} in the American nomenclature. (over five cutoffs)

$$R_z[DIN] = R_{tm} \tag{3.14}$$

R_z(ISO) - Ten Point Average Roughness

R_z(ISO) is a parameter that averages the height of the five highest peaks plus the depth of the five deepest valleys over the evaluation length.

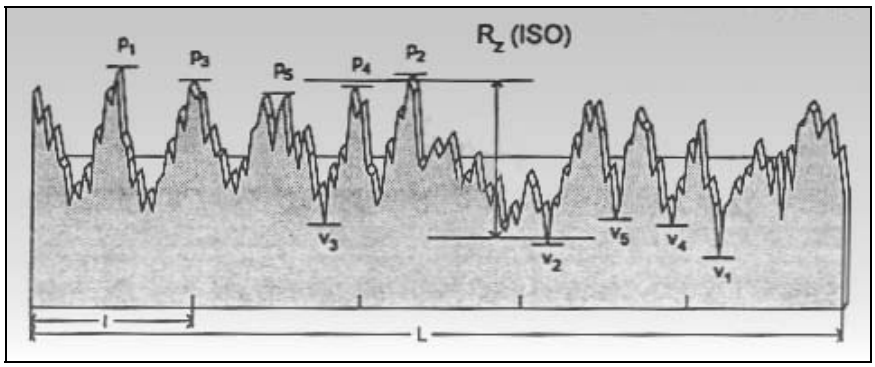


Fig. 3.10 Rz (ISO)

3.4.2 Roughness Spacing Parameters

S_m - Mean Spacing

S_m is the mean spacing between peaks, with a peak defined relative to the mean line. A peak must cross above the mean line and then back below it.

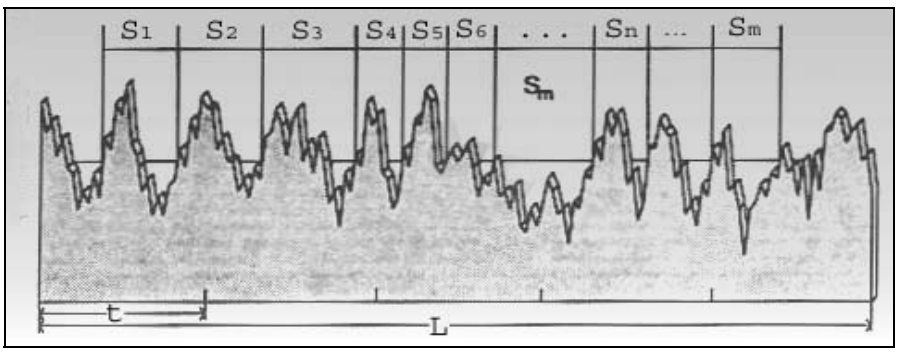


Fig. 3.11 Mean Spacing - Sm

If the width of each peak is denoted as S_i (above), then the mean spacing is the average width of a peak over the evaluation length:

$$S_m = \frac{1}{N}\sum_{n=1}^{N} S_n \qquad \text{(Eqn. 3.15)}$$

S_m is usually reported in μin or mm.

λ_a - Average Wavelength

The average wavelength of the surface is defined as follows:

$$\lambda_a = 2\pi \frac{R_a}{\Delta_a} \qquad \text{(Eqn. 3.16)}$$

where Δ_a is Average Absolute Slope. This parameter is analogous to S_m in that it measures the mean distance between features, but it is a mean that is weighted by the amplitude of the individual wavelengths, whereas S_m will find the predominant wavelength. [6]

λ_q - RMS Average Wavelength

$$\lambda_q = 2\pi \frac{R_q}{\Delta_q} \qquad \text{(Eqn. 3.17)}$$

where Δ_q is rms average slope.[6]

3.5 Principles of Roughness Measurement

Measurement means something more than mere inspection. Measurement can be defined as a process which gives, or is capable of giving, quantitative information about individual or average surface heights. But many forms of optical examination is excluded. These may give information about the existence and direction of the lay on machined surfaces, or about the presence and spacing of feed and chatter marks or other individual defects, but this does not fall within our definition.

There are some general considerations in choosing any measuring instrument: cost, ease of operation, size and robustness. There is also the issue of whether a measurement is comparative or absolute. In addition, for roughness measuring instruments, it is necessary to decide whether or not the instrument should make physical contact with the surface, and whether it needs to be able to measure an area of a surface or only a section or profile through it. Most important of all are the horizontal and vertical range and resolution.

Some of these criteria are self-explanatory, but the issue of comparative versus absolute measurement is worth a few moments digression. Many roughness measuring instruments, for instance stylus instruments, give absolute measurements of local heights. Thus they can be calibrated against secondary length standards such as slip gauges and so in principle at least are traceable to primary standards. Other instruments, for instance glossmeters, give average values of some surface parameter, which may depend on material properties and may vary from one finishing process to the next. Such instruments must be calibrated against an absolute instrument used under the same conditions. Under these conditions they may still be traceable, but in a much more tightly restricted way. This is likely to be of some practical importance in a manufacturing environment where the roughness instrument is part of a quality system under ISO 9000.

Sectional measurement is usually quicker, simpler and easier to interpret than a real measurement, and all current roughness standards, are written in terms of sectional measurements. For many practical purposes sectional measurements are adequate, and sectional techniques should be preferred unless there is some good reason to the contrary. However, most engineering interactions of surfaces, including all contact phenomena, are a real in nature, and the information necessary to describe their function must similarly be a real. Often this information can be inferred mathematically from sectional information.

3.5.1 Main Measurement Methods of Surface Roughness

Inspection and assessment of surface roughness of machined work pieces can be carried out by means of different measurement techniques. These methods can be ranked into the following classes:

- Direct measurement methods
- Comparison based techniques
- Non contact methods
- On-process measurement

Direct Measurement Methods

Direct methods assess surface finish by means of stylus type devices. Measurements are obtained using a stylus drawn along the surface to be measured: the stylus motion perpendicular to the surface is registered. This registered profile is then used to calculate the roughness parameters. This method requires interruption of the machine process, and the sharp diamond stylus may make micro-scratches on surfaces.

Comparison Based Techniques

Comparison techniques use specimens of surface roughness produced by the same process, material and machining parameters as the surface to be compared. Visual and tactile senses are used to compare a specimen with a surface of known surface finish. Because of the subjective judgment involved, this method is useful for surface roughness Rq>1.6 micron. [7]

Non Contact Methods

There have been some works done to attempt to measure surface roughness using non contact technique. Basic example can be given as following. When coherent light illuminates a rough surface, the diffracted waves from each point of the surface mutually interfere to form a pattern which appears as a grain pattern of bright and dark regions. The spatial statistical properties of this speckle image can be related to the surface characteristics. The degree of correlation of two speckle patterns

produced from the same surface by two different illumination beams can be used as a roughness parameter.

The following figure shows the measure principle. A rough surface is illuminated by a monochromatic plane wave with an angle of incidence with respect to the normal to the surface, multiscatterring and shadowing effects are neglected. The photosensor of a CCD camera placed in the focal plane of a Fourier lens is used for recording speckle patterns. Assuming Cartesian coordinates x,y,z, a rough surface can be represented by its ordinates Z(x,y) with respect to an arbitrary datum plane having transverse coordinates (x,y). Then the rms surface roughness can be defined and calculated.

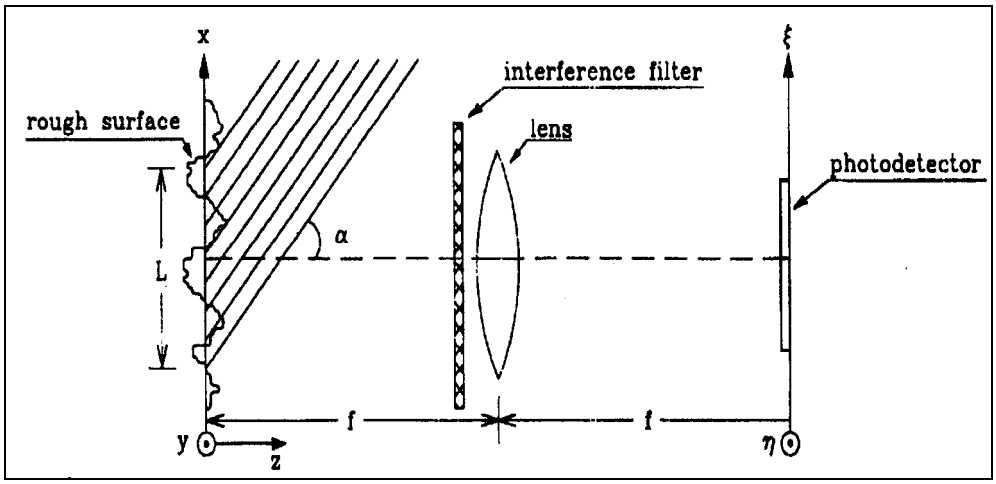


Fig. 3.12 Measuring Principle of Non Contact Method

On-process measurement

Many methods have been used to measure surface roughness in process. For example:

Machine vision: In this technique, a light source is used to illuminate the surface with a digital system to viewing the surface and the data being sent to a computer to be analyzed. The digitized data is then used with a correlation chart to get actual roughness values.

Inductance method: An inductance pickup is used to measure the distance between the surface and the pickup. This measurement gives a parametric value that may be

used to give a comparative roughness. However, this method is limited to measuring magnetic materials.

Ultrasound: A spherically focused ultrasonic sensor is positioned with a non normal incidence angle above the surface. The sensor sends out an ultrasonic pulse to the personal computer for analysis and calculation of roughness parameters.

3.6 Profile Measuring Lengths in Direct Measurement Methods

Traverse Length

The traverse length (A+B+C) of a profile measurement is the total distance traveled by the profiling instrument's pick-up during data collection.

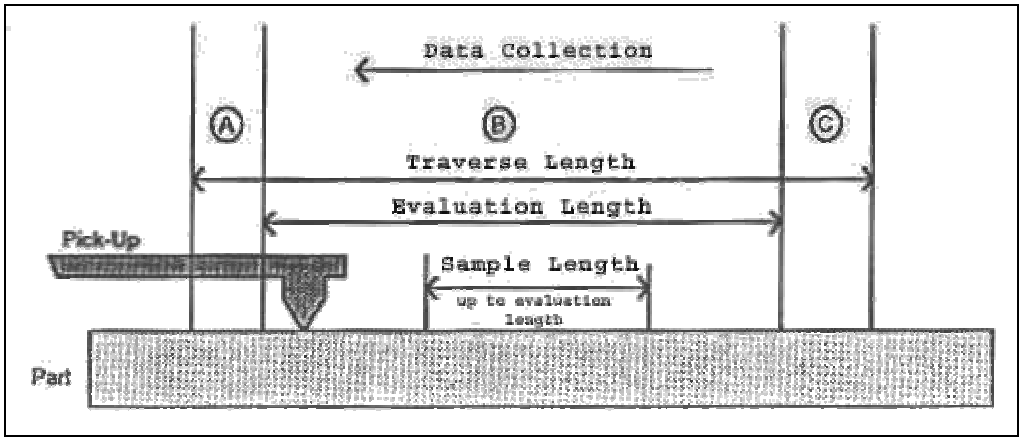


Fig. 3.13 Profile Measurement

Evaluation Length

The evaluation length (B) is the entire length of a profile over which data has been collected. The evaluation length will ordinarily be shorter than the traverse length because of end effects in the travel (A) and (C): motors accelerating and decelerating, electrical filters settling down, etc. Evaluation length is denoted as L.

Sample Length

For roughness measurements one evaluation length consists of several (ordinarily five) sample lengths. Many roughness parameters are statistical averages of values for the individual sample lengths.

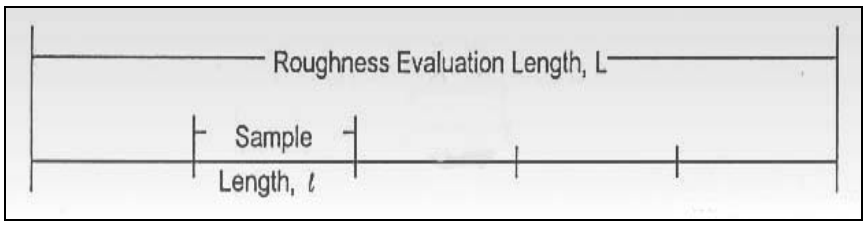


Fig. 3.14 Evaluation Length

For waviness and form error measurements, the sample length is usually chosen to be equal to the evaluation length, but there is presently no standard way of defining the sample length or per-sample-length parameters for these profiles. For waviness an emerging standard for the waviness evaluation length (and waviness filter cut-off) is ten times the roughness cutoff.

A single sample length is denoted l. For the roughness profile the sample length is almost invariably chosen to be equal to the cutoff length of the roughness filter.

There is often not a clear distinction made between the sample length and the evaluation length, even within a particular instrument manufacturer. Another term which usually equates to evaluation length is "assessment length".

In order to measure any modified profile, it will be needed to measure more of the surface than your final evaluation length, and the portion of the surface that you measure is always shorter than the portion of the surface that you physically traverse.

3.7 Schematic of a Surface Profiling Instrument

The Instrument Measuring Loop

The measuring loop of an instrument comprises all of the components of the instrument and fixturing that contribute to converting the real surface profile into an electrical (analog or digital) representation of the profile.

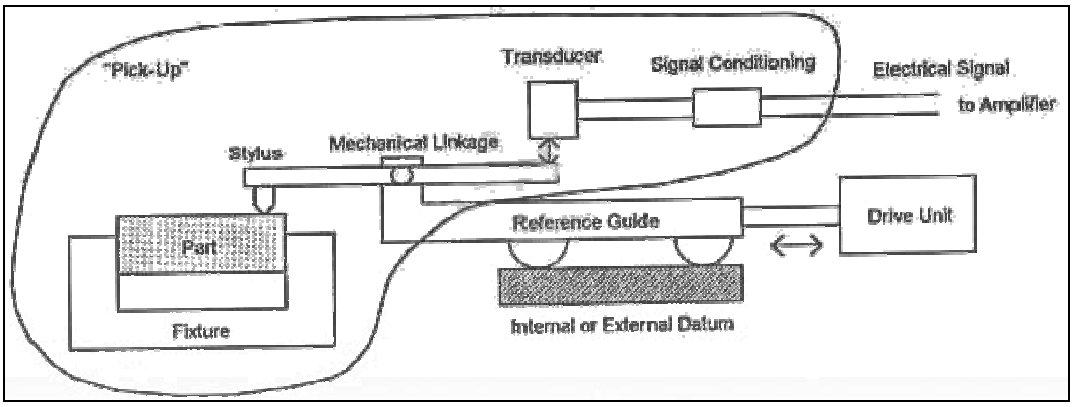


Fig. 3.15 The measuring loop of a profiling instrument

Internal (Skid) Reference Datum

Several methods can be used to establish an instrument reference line from which profile height can be measured. The simplest approach is to use a skid riding on the surface itself as a reference. Usually the arm to which the skid is tied pivots a long distance away from the measurement. The skid assembly and transducer are designed to measure the difference in height between the skid height and the stylus tip height. The skid rides over imperfections in the surface and acts as a mechanical filter of the surface: it smoothes out longer wavelength undulations in the surface. This approach is therefore suitable for roughness profile measurement only.

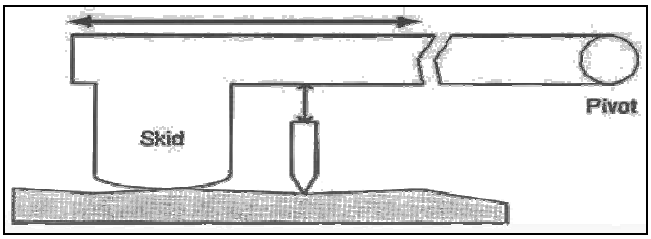


Fig. 3.16 Skid Profiling Instrument

Several alternatives are in use for the geometry of the skid relative to the stylus tip. A single skid can ride in front of, behind, or in line with the diamond. More commonly two skids are used that ride on either side of the diamond. A final alternative is a single skid with the diamond tip protruding down from its center.

For some applications, for example measuring round parts, it may be desirable to use two skids to establish the reference height, eliminating the pivot from the measurement.

CHAPTER 4

VARIABLES AFFECTING ULTRASONIC TEST RESULTS

4.1 Introduction

Ultrasonic tests can provide information about several aspects of a material such as: thickness, attenuation, shape, presence of defects, size and their orientation. These rely on two main measurements: amplitude of signal and time of the signal arrival. To a lesser extent the frequency content of the signal can also provide useful information but its application is not so common.

While testing, some certain assumptions about the test conditions are made and presume that changes in time or amplitude are caused by variation in the parameter of interest. The assumptions made are based on all parameters being constant except the one we are interested in measuring changes in. For example, when performing a thickness measurement, the acoustic velocity of the test piece which is being measured is assumed the same as the acoustic velocity in the calibration piece. And it is also assumed that the temperature at which tests and calibrations are made are not important. Both of the parameters which are assumed fixed can affect our test results by changing sound propagation velocity in the material. Variables affecting the test results will be divided into 4 groups:

1. Instrument Performance
2. Transducer Performance
3. Material Variations
4. Defect Variations

Another factor relating to the results of an inspection is the Human Factor; this is a widely debated subject and it will be not mentioned here because it is related with the subject of Probability of Detection.

4.2 Instrument Performance

Scope - The primary variable in the scope is the linearity of the time base. Verification methods will usually require a tolerance in accuracy to a percentage of the total screen range (typically +/- 2%). This ensures no distance measured will be in error by more than 2%, e.g. for a 250mm range it may be possible to have an error of +/-5mm maximum in steel. [8]

Pulser-Receiver - Amplitude uncertainties will result from variations in the linearity of the vertical deflection of the scope or due to inaccuracies in the amplitude control. Scope vertical linearity ensures that the relationship between two signals of different amplitudes is maintained over the entire range of the screen height. This is done by comparing the relative height of two echoes at different screen heights. e.g. setting two echoes 6 dB apart starting with one at 80% FSH, the other at 40% FSH adjustments are made to first increase the 80% FSH signal to 90% and 100%. The lower signal should be 45% and 50% respectively. Reducing the higher signal in 10% FSH increments, the lower should continue to be half its height. Tolerance for this parameter is +/-5% of the screen height. This ensures that the signal ratio of two different amplitudes truly indicates the size or distance effects. This would be most important for DGS type comparisons.

The other aspect of vertical linearity variability is the amplitude gain control. This applies to the calibrated gain control usually found in dB increments on a flaw detector. Since the dB is derived from (dB = 20 log A2/A1 changing the dB gain by a fixed amount should change the ratio of the signals. This allows us to expect a signal at 50% FSH to increase to 100% FSH when 6dB is added to the receiver gain. ASME code requires scanning of a weld to be done using 14dB over reference. This means a signal that was 20% of the reference amplitude at reference gain would then come up to the reference level denoted by the DAC. If the receiver gain is not linear the smallest recordable indication may be greater or less than the intended level. This will be another source of incorrectly sizing a defect with respect to a reference.

4.3 Transducer Performance

As with the pulser/receiver, transducer performance have to be checked and monitored for change. To ensure any change is within tolerances allowed initially, they must all be monitored on a regular basis to ensure no significant changes occur. BS 4331 Part 3*, recommends the following probe/system performance checks; [8]

Table 4.1: Probe/System Performance Checks

ITEM	MONITORING FREQUENCY
probe index	daily on rough surfaces, such as castings, twice daily
beam angle	
beam skew (squint)	
beam profile	monthly and when large changes in probe angle or index are observed
dominant frequency	monthly and whenever repairs have been made to either probe or instrument and if one instrument is replaced with another
pulse length	
dead zone	
near field	
signal-to-noise ratio	
overall system gain	daily and after repairs or replacement as above
resolving power	monthly and after repairs or replacement as above

The above monitoring items apply to contact testing probes. The wear experienced by movement on metal surfaces tends to accelerate changes in performance. Some of the changes introduced by wear can alter test results significantly. Beam angle for

In the chart of items checked as per BS 4331, the first three items are unique to contact probes, but the remaining items could be considered by any transducer evaluation, including immersion probes. Handling and aging can cause changes to the element's backing, degree of polarization, lensing material shape, lens material bond to the element or degree of loading. These changes result in changes in both amplitude and frequency. The effect on performance is multi-stepped. [8]

For example: if aging has resulted in a slight disbonding of the element from the high density backing of a standard ceramic element, its damping will be reduced. This will lead to an increased ringing. More ringing reduces resolution and increases the extent

of dead zone due to the rattle. Decreased damping due to the disbondment, however, allows vibrations to be larger so sensitivity is increased. The reduction in backing load tends to change the centre-frequency to a higher value but the increased sensitivity, afforded by more and larger vibration displacements, reduces the bandwidth. The higher frequency increases the near zone as it is a function of wavelength. The angle of divergence is also changed (decreased) as it is a function of wavelength too. [8]

Operating probes in warm water (>50°C) or high radiation fields (several MegaRads) can cause blistering or disbonding of the epoxy material used for lensing. This could have similar effects to those noted for backing disbondment as well as distorting and redirecting the beam centre-line. [8]

In addition to aging and environmental causes of alterations to the transducer performance, handling can also cause changes to occur. A sharp jolt from dropping a probe may result in similar disbond problems. With the availability of different pulse shapes it may be possible to deteriorate polarization in an element. A negative going pulse voltage is normally applied to probes but polymer elements tend to perform better with a positive going pulse. Polymer probes will show no deterioration if pulsed with negative going spikes but ceramic elements may experience depolarization over extended periods of time. Depolarization will reduce sensitivity and the increased gain required will manifest itself in a lower s/n ratio. [8]

Sources of variation in transducer performance are many. Establishing a baseline with tolerances and then monitoring for changes in any of the parameters checked will help to ensure reliability of test results.

4.4 Material Variations

When considering the variables of the test material that affect test results, it can be grouped into three areas of concern:

1. Entry surface
2. Part size and geometry
3. Internal structure.

Entry surface variables include:

1. Surface roughness
2. Surface coatings
3. Couplant condition.

4.4.1 Surface Roughness

Surface roughness will have several possible effects on the inspection of a test piece. In contact testing, roughness on a gross scale results from: weld spatter, plate scale, dirt (sand) and rough cast surfaces from sand casting and different rough surfaces occurred from various machining operations. These irregularities will cause some points of contact to push away the couplant and force it into the lower areas around the probe. If the couplant is not sufficiently viscous it will drain away quickly and fail to couple the probe to the test piece.

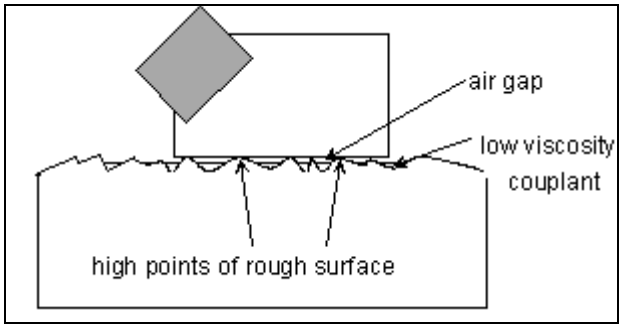


Fig. 4.1 Poor coupling results due to rough surface and thin couplant

In addition to reduced coupling, which will reduce signal amplitudes, the rough surface increases the rate of wear on the probe. On an otherwise smooth surface isolated sticky regions such as weld spatter can hinder or stop probe motion or in the case of mechanized systems there may be sufficient force to move the probe past the obstruction but this could result in damaging the probe by either tearing it from its mounting or severely scoring the plastic wedge. When the dirt on the test piece is very fine (similar to a flour texture) coupling can be prevented due to surface tension preventing the liquid couplant penetrating to the metal. Unless a transfer value has been established between test piece and calibration piece, this could go undetected.

In addition to affecting coupling, surface roughness tends to reduce signal amplitude by scattering and focusing the beam. This applies to both contact and immersion testing.

Whether uniform or irregular, a rough surface has the potential to present a scattering effect at an interface where a beam impinges. The degree of scattering is based on the ratio of roughness to wavelength. When roughness is less than about 1/10 a wavelength, scatter will be negligible. To reduce signal losses due to scattering an operator can select a lower frequency probe. In addition to signal reduction another effect of surface irregularities is to redirect and mode convert some energy which when returned to the probe can be the source of spurious signals. In contact testing false indications from standing waves resulting from scatter on rough surfaces will normally have short sound paths. They can be eliminated as true flaws by failing to locate any trace of indication from the full skip or from the opposite side. [8]

Unless done properly, removal of surface roughness by mechanical means can result in further scattering problems. Small curved gouges left by a grinding wheel used to remove spatter or machining grooves can form small lenses. The affect of grinding can be unpredictable. Some of the lensing may concentrate the beam thereby increasing signal amplitude, or, the lens effect may be a de-focusing of the beam, again resulting in lower than expected signal amplitudes. Uniform surface preparation by sand or shot blasting usually provides a good surface for ultrasonic testing. Removal of excess metal by a hand held grinding wheel is commonly used on weld caps and roots. When a pipe weld has had its root ground flush and inspection can only be performed from the outside diameter, quality of grinding can result in unnecessary repair calls if grinding has been along the weld axis. The small grooves made by the grinding wheel run parallel to the root edge and are easily confused with lack of fusion, missed edge or undercut defects. [8]

4.4.2 Surface Coatings

Surface coatings are added to protect a surface from corrosion or to enhance its appearance. Thin films, such as oxide layers, anodizing layers or electroplated finishes, and the slightly thicker coatings of paint or lacquer are usually well bonded

to the surface. Quality of bond may be compared to the uncoated reference block by a simple transfer value. Even a slight loss due to the coating may be preferable to removing the coating and trying to inspect on the rough surface it hides.

4.4.3 Coupling Condition

Both contact and immersion methods utilize intervening media to transfer sound from the probe into the test piece and back to the receiver. With immersion methods it is accomplished by a single fluid medium. In contact testing there are nearly always at least two intervening media; the delayline or protective face and the thin film of coupling fluid or grease. Attenuation and acoustic velocity are the two main properties that dictate the performance of a couplant. Attenuation affects amplitude of the signal and velocity will determine both transit time and refracted angles.

But attenuation and velocity of couplants are not independent properties. Each is a function of other parameters. Unless these parameters are controlled or in some way compensated for, gross variations from the reference value or calibration conditions can result.

Attenuation of couplants varies with material composition as would be expected. Published attenuation values are available for many materials as indicated in the table below. Attenuation coefficients are often quoted in dimensionless number nepers which allow for frequency dependence or in dB/mm. [8]

1 Np = 8,686 dB 1 Np/cm = 0.87 dB/mm [4]

For water, attenuation is about 5 dB per meter. Since such long water path lengths are not normally used the 0.005 dB/mm attenuation is considered negligible. But for the heavier oils attenuations 200 to 500 times greater can have significant effects on signal amplitude and frequency content. [8]

Attenuation is not a material constant. Under changes in conditions it can change. For example attenuation in water is inversely proportional to both temperature and pressure.

At standard pressure and temperature (1 atmosphere and 20°C) attenuation in water is 25.3 x 10^{-15} Np. When temperature is 0°C and water still liquid attenuation is 56.9 x 10^{-15} Np and at 40° it is 14.6 x 10^{-15} Np. At 1000 atmospheres attenuation drops to 12.7 x 10^{-15} Np and increases to 18.5 x 10^{-15} Np in a vacuum (zero atmospheres) when the temperature is held at 30°C. [8]

Attenuation of couplants need rarely be considered when calibration and test conditions are the same couplant material, temperature and pressure. However, mechanical actions can add to variations in attenuation under some conditions e.g. liquid soap is often used in contact testing. Under static conditions it provides reasonable coupling, ease of probe movement and clean hands. When a part is inspected with more rapid probe motion than may be used for static calibration it is possible to lather the soap. As bubble density builds in the couplant attenuation will increase.

4.4.4 Part Size and Geometry

Test results may vary if the test piece differs from the calibration or reference piece. In this way both shape and size will contribute to potential variation in test results. Particular interest in this variable exists for contact testing on curved surfaces. When a flat probe is used on a convex curved surface only a portion of the probe makes contact. This will reduce the amount of sound that can be transferred to and from the test piece. As a result sensitivity compared to coupling to a flat piece is reduced. The proportion of sound reduction compared to a flat piece is a function of the curvature of the part, the crystal diameter and the coupling ability of the couplant via its viscosity. To avoid machining calibration blocks for every possible radius and surface condition compensation is made by adding gain to the receiver. The amount of compensating gain can be determined by a simple transfer value or it can be calculated using formulae and charts.

4.4.5 Internal Structure

The final aspect of material variations affecting test results is the structure of material under test. Material parameters are a function of makeup and environmental

conditions. Makeup is determined by design and processing. Whether the material under test is steel, aluminium or fibre-composite, variations can occur by design. Proportion of resin to fibre will vary in composites and metals may have many alloying variations. In addition, metal grain structure can be varied by alloy, heat treatment and working. All these factors will provide differences in the results of ultrasonic tests manifested as variations in velocity or attenuation. Also, just as temperature and pressures were noted to change velocity and attenuation in couplants so too will the material under test be similarly affected by these externally controlled conditions.

Just as with surface roughness, scatter will be a function of wavelength. Krautkramer points out that for grain sizes up to about 1/100th of a wavelength scatter can be considered negligible. However, as grain size increases beyond that, it can become a significant factor adding to decreasing signal amplitudes. As grain sizes increase to greater than 1/10th the wavelength, inspection may not be possible by ultrasonics. Austenitic stainless steels are typical of metals with large grain structures. In the production of austenitic steels manufacturers often attempt to control or limit grain size. This is done by :

a) introducing small amounts of grain refining elements

b) limiting the temperature the steel is heated to

c) hot working the steel to break up the austenite grains

Finally, as with couplants, acoustic velocity of a test material varies with temperature. Most published values will indicate velocities determined at 20°C. For work at much higher or lower temperatures corrections will need to be made. This will require the temperature dependence for the material to be established and this will have to be in addition to similar corrections made for couplant changes.

4.4.6 Defect Variation

The next major factor affecting test results is the defect or reflecting surface of interest. In evaluating a signal an operator will use three items; soundpath, probe position and amplitude. The change in relationship of these three aspects is called "echo dynamics". Therefore, investigating the echo dynamics of a flaw allows the

operator to build up an image (mental in manual scanning and possibly visual if automated) of the shape of the flaw. Four factors are significant in the response obtained from a defect;

1. Size and geometry

2. Location with respect to adjacent surfaces

3. Orientation of the major axis

4. Type of discontinuity and conditions of reflection.

Defect Size and Geometry

Both defect size and defect shape have a significant affect on signal amplitude. Generally small defects provide smaller amplitude signals than larger flaws. However, an irregular flaw shape may mean not all of the flaw reflects the sound back to the receiver. Irregular facets of a crack or close proximity of pores in clusters of porosity can result in sufficient losses due to scatter that very small signals are received in spite of the fact that a large volume of metal is missing; i.e. signal amplitude is no guarantee of defect size.

Location with Respect to Adjacent Surfaces

Defect position with respect to adjacent surfaces presents several causes of variable results. Simple attenuation accounts for reduced signal amplitude by increasing the sound path (in the far zone) to the flaw. If the flaw is close to another reflecting surface confusing signals may result or signals may be lost.

Orientation of Major Axis

When the major axis of a defect is not exactly perpendicular to the beam reflection causes the returned signal to be directed away from the simple return path back to the transmitter. For small angles this will not cause a total loss of signal as beam dimensions are sufficient that the off-centre portions can still be detected by the probe. Even small angles off normal(e.g. +/-5°) can result in significant signal reductions. When expected flaws are planar and no convenient pulse-echo angle can

be arranged to ensure the beam will strike the flaw at right-angles tandem probe arrangements are preferred. [8]

Type of Discontinuity and Conditions of Reflection

To some extent this has been addressed by the other aspects. Defect size and geometry is usually determined by its type; e.g. porosity is usually small and spherical, slag is irregular in shape and size, and non-fusion is usually planar. However, reflectivity of defects is not a simple matter of incident angle. For very fine porosity there may be no noticeable back reflected signal but the scatter such a dispersive defect would cause would reduce the transmitted energy. But maximum reflection occurs off a free boundary. This is effectively the situation for non-fusion and cracks where the void is air. However, when a dissimilar material fills the void, as would be the case in a slag inclusion or tungsten inclusions in a TIG weld or carbide inclusions in castings or forgings, part of the sound incident on the boundary is transmitted. This will reduce the reflected signal. Added to the loss due to transmission into the next medium is the associated loss due to the reflection at any angle other than 0°.

CHAPTER 5

EXPERIMENTAL STUDY

5.1 What is in Literature

Several studies are made in the literature to find the exact effect of surface roughness on ultrasonic test results and to reveal a correlation between them. But each study examined the different points of the case, by means of different types of probe and frequency usage, by means of different test technique (immersion and contact), by means of different roughness style (random or periodic roughness) etc. But in each study, it is said to be that roughness affects ultrasonic beam in certain amount depending on the frequency, roughness and technique used. Having based on these studies, the effect of periodic rough front surfaces on ultrasonic testing and discontinuity detection capability of rough surfaces are examined by experiments in this study. To get more information about the phenomena, tests are made by using different type of couplants and probes having different frequencies. Some of the major studies from literature and their results are given in the following paragraphs.

Effect of front (entry) surface roughness on the reflected signal amplitudes and the characteristics of the signal features in ultrasonic testing (UT) are examined in the study by M.Thavasimuthu, C.Rajagopalan, T.Jayakumar and Baldev Raj **[9]**. Experiments were carried out with specimens having different size of holes along a certain depth and having various surface roughness values. Specimens were made of stainless steel with 210 x 80 x 20 mm. dimensions. The roughness of one major face of the specimen was varied for different specimens, while the roughness of the other major face was kept constant for all the specimens. Different roughness values (6, 12, 25, and 50 μm rms) were achieved by grinding operation using various grit size abrasive tools. The roughness measurements were carried out using a stylus displacement technique. Side drilled holes with different diameters 2, 3, 4, and 5 mm and a constant depth of 40 mm were introduced as artificial discontinuities in each

specimen to simulate naturally occurring ones. An ultrasonic discontinuity detector, along with normal beam narrow band probes of frequencies 2, 4, 8 MHz and glycerin gel was used in the experiments. And as a result it is concluded that surface roughness plays a major role in altering the properties of the transmitted and reflected ultrasonic signals. And the problem of ambiguity in quantitative sizing of discontinuities when there is a change in the surface roughness, and the necessity for using two test frequencies to overcome the problem, has been discussed in the study.

The effect of surface roughness (1 to 23 μm rms) on the amplitude of ultrasonic echoes has been studied for longitudinal waves in steel over a frequency range 1, 2.25, 5, 10, 15, 20 Mhz by G.V.Blessing, P.P.Bagley and J.E.James **[10]**. Total set of 7 samples consisted of four with their roughness machined by a shaper, one by grinding, one by bead blasting and one by grit blasting. The samples were fabricated from M50 (High speed tool) steel in shape of disks of approximately 10 cm diameter and 1,9 cm thickness. All samples possessed a smooth ground finish on their back surfaces. For the transducer, immersion and airbone ultrasound transducers are used. And as a result over the range of available surface roughness values, an apparent increase in ultrasonic attenuation as a function of roughness was observed in steel at the higher frequencies studied from 10 to 20 MHz. No such effect was observed at lower frequencies studied from 1 to 5 MHz. Front surface reflectivity measurements as a function of roughness yielded the same results whether using airbone or water immersed ultrasound for an equivalent wavelength for that medium.

The problem of ultrasonic transmission and reflection at a randomly rough interface is considered in connection with ultrasonic NDE of rough surface samples by immersion method by Peter B.Nagy, Laszio Adler [13]. Sand blasted aluminum samples having 25 mm. thicknesses are used in the experiments. The 12.5 mm. diameter transducer is placed 100 mm at normal incidence. As a result the surface roughness induced attenuation mainly depends on the rms roughness, but, in case of strong roughness it becomes increasingly dependent on the surface profile as well. And in case of water aluminum interface, the transmitted wave is much less attenuated than the reflected one.

5.2 Experiments

The experimental part of the study includes the route followed from the beginning till the end of experiments. Each step is explained briefly as the following order.

1) Material Selection and Material Properties
2) Test Specimens
    - Surface Preparation
    - Roughness Measurement
    - Side Drilled Holes
3) Ultrasonic examination results by using machine oil as a couplant
4) Ultrasonic examination results by using grease as a couplant

5.2.1 Material Selection and Properties

Today, several types of materials are in use through the demand of industry. There are many steel types used for different type applications and so for the other materials like aluminum, stainless steel etc. It will be difficult to compare different types of materials in the same test because every material behaves different under same machining conditions and there might be trouble obtaining same rough surfaces with different material. So choosing a material which is used more frequently and which is available for different machining operations will be better for our study. By considering these two criteria, it is planned to carry out the experiments with AISI/SAE 1040 steel, because of its frequent usage and availability for different machining operations.

General Information on AISI/SAE 1040

It is a general purpose mild steel with medium-carbon fine grain suitable for machinery parts. In the production of this grade, special controls are used for chemical composition, heating, rolling and surface preparation. These bars are suitable for applications of forging, cold drawing, machining, and heat treating (including flame hardening). Good wear resistance can be obtained by flame or induction hardening. Below table shows the chemical composition of the AISI/SAE 1040 steel **[25]**

Table 5.1 Chemical Composition of AISI/SAE 1040 steel [25]

AISI/SAE NORM		1040		
DIN NORM		C 35		
C	**Mn**	**Si**	**P**	**S**
0,35 0,44	0,60 0,90	0,10 0,30	Max 0,040	Max 0,050

Typical applications

Transmission axles, bolts, shafts, machinery parts, lightly stressed gears, pinions forming dies and rails.

Mechanical properties

The following values are average values and may be considered as representative.

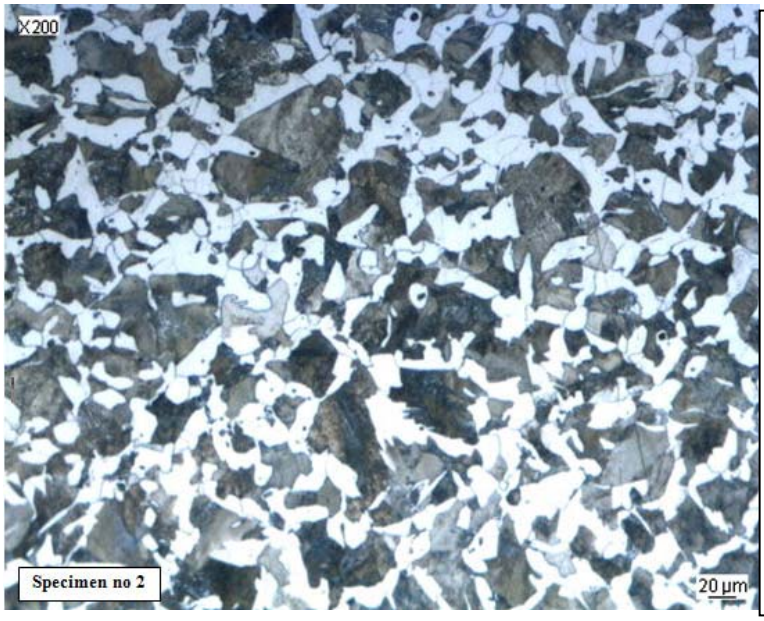
Table 5.2 Average values of mechanical properties of AISI/SAE 1040 steel

Tensile strength	MPa	600 - 800
Yield strength	MPa	330 - 420
Elongation	%	16 - 25
Reduction in area	%	49
Brinell hardness		180

5.2.2 Test Specimens

AISI/SAE 1040 steel specimens bought for the experiments were manufactured in Karabük Demir Çelik Factory and hot rolled in another factory to obtain different cross-sections. All specimens were cut from the same batch to ensure that they will show the same characteristics. The raw material was 60×60 mm in cross section, and 4 pieces were cut each having a length of 300 mm. The real specimens are planned to be 150 mm in length but in order to obtain same roughness value at two set of specimens, they were cut together to apply machining at the same time. This reduced the deviation in roughness values between specimens of the same set.

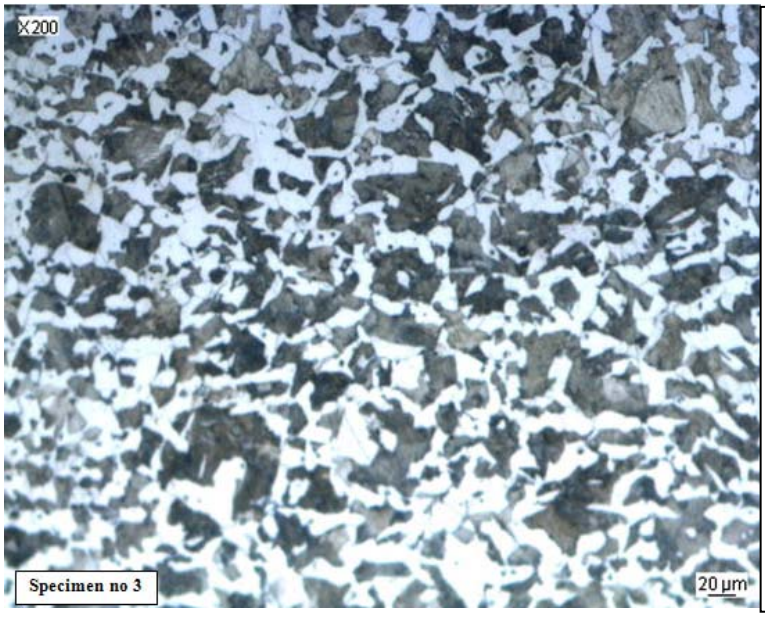
To be sure about material properties of the test pieces with the literature values, they are subjected to microstructural analysis. Three random pieces were cut from specimens for the analysis. After grinding, polishing and etching operations, the photos were taken to examine the microstructure as in Fig.5.1-2-3 with Leica Microsystems at Bosch San.Tic.A.Ş - Bursa. Grain size, pearlitic and ferritic structures were in correlation with the literature datas. Chemical composition was analyzed by Thermo ARL Iron Steel Metal Analyzer device again at Bosch-Bursa.



Chemical Composition

	Averg.
C	0.37629
Mn	0.77723
Si	0.24072
P	0.01784
S	0.03730

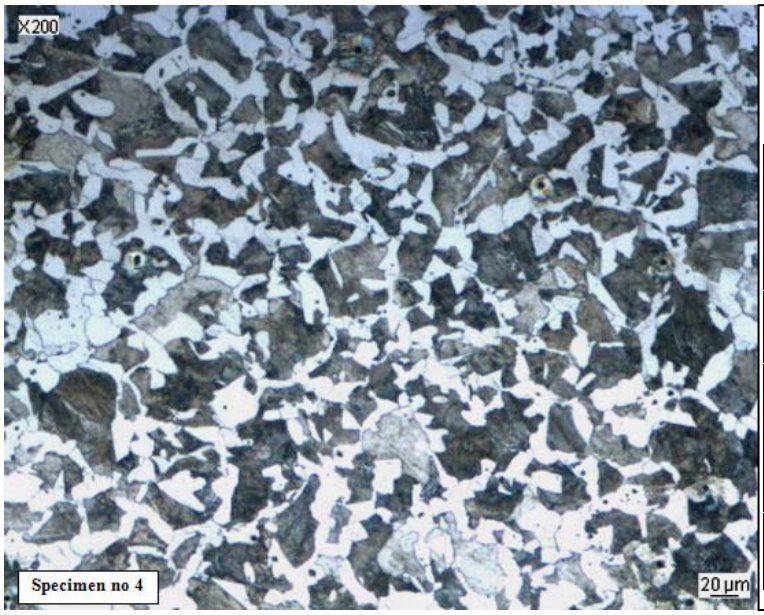
Fig.5.1 Microstructural view at 200X magnification and chemical composition of specimen 2



Chemical Composition

	Averg.
C	0.36714
Mn	0.76993
Si	0.23884
P	0.01790
S	0.03524

Fig.5.2 Microstructural view at 200X magnification and chemical composition of specimen 3



Chemical Composition

	Averg.
C	0.37947
Mn	0.78556
Si	0.24336
P	0.01550
S	0.03176

Fig.5.3 Microstructural view at 200X magnification and chemical composition of specimen 4

Then, the specimens were brought to nondestructive testing laboratories of METU for prior inspection. This step was taken to ensure that specimens had no discontinuity which might affect the test results later. 4 pieces of 60×60×300 AISI/SAE 1040 steel blocks were ultrasonically examined by Krautkramer 4 MHz straight beam probe after calibrating Krautkramer Branson USK7B device. No abnormalities were detected after examining the pieces from two sides.

Surface Preparation

Several methods were used to obtain appropriate surface roughness. The point here is that, nearly every machining operation forms its own roughness, lay, waviness style. And choosing a widely used machining operation is important to reference actual industry situations. Milling is a very conventional tool used in most areas of machinery and it is a widely used operation. It is possible to change surface quality by altering the parameters of the milling machine. There are three main parameters that surface roughness is directly proportional; feed rate, depth of cut and spindle speed. **[28]** By changing these, 4 different surfaces having different roughness values are formed at one side of the specimens. The machine used for machining the surfaces was a universal milling machine having certain parameters which can be applied manually. The head part of the milling machine was tilted to a very small angle to prevent cross arcuate lay structure. By tilting, the resultant lay would be

arcuate lay structure. The tool used for milling operation was a 10 cm. diameter tool with single diamond on it. The machine parameters and obtained roughness values are given below.

Table 5.3 Milling machine parameters and roughness values obtained

SPECIMEN SET 1				
Spindle Speed	630 (rpm)		Roughness (Ra - μm)	3,00
Feed Rate	250 (mm/min)			
SPECIMEN SET 2				
Spindle Speed	400 (rpm)		Roughness (Ra - μm)	4,50
Feed Rate	315 (mm/min)			
SPECIMEN SET 3				
Spindle Speed	630 (rpm)		Roughness (Ra - μm)	11,00
Feed Rate	400 (mm/min)			
SPECIMEN SET 4				
Spindle Speed	315 (rpm)		Roughness (Ra - μm)	26,50
Feed Rate	500 (mm/min)			

Only one side of each specimen was machined with these parameters. The other sides were also machined but only for removing rust from the surfaces and they were grounded afterwards. The machined surface of Specimen set 1 (having 3,00 μm Ra) is grounded by a surface grinding machine in order to reduce its roughness value to 0,5 μm Ra . Then all specimen sets were put on their machined surfaces downward to the table of grinding machine and back sides of every specimen was grounded by the same surface grinding machine, at the same time. This made specimens to have same height and same roughness value at back surfaces. In order just to have a clean surface for the other 2 faces which are not grounded, grinding operation is applied coarsely. At the end of these processes, top view of the specimens were as in following photo.

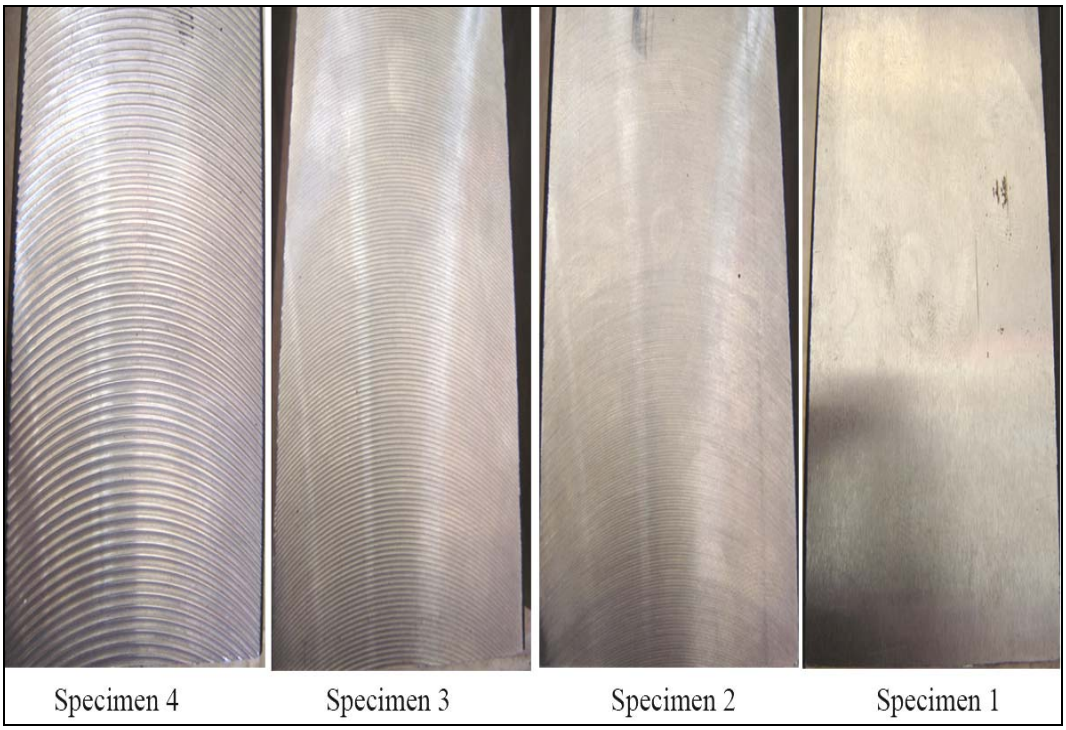


Fig.5.4 Top view of the specimens after machining processes

Roughness Measurement

Roughness measurements are made by Mitutoyo Suftest 211 Series 178 device which belongs to METU BİLTİR CAD/CAM Center located at Mechanical Engineering Department. It is a precision device that can measure average roughness by a stylus displacement technique up to 40 μm Ra. Technical specification of the device is given at Table 5.4. The first thing done with the instrument before roughness measurement was the calibration. There was a calibration block supplied with the instrument having arcuate lay structured roughness profile with the value of 3.05 μm Ra. Calibration is done before starting experiments, after every ten measurement and before measuring the next specimen. The main point of roughness measurement is to locate the detector of the instrument correctly in order to move perpendicular to the lay direction. Fig.5.6 shows the direction and measurement points at different locations on the test specimens.

To fully describe the surface, photos were taken with a device, technoscope (Leica Microsystems at Bosch San.Tic.A.Ş. – Bursa) which can magnify a view with a scale, that enables to take more measurement from rough surfaces through that view like peak to peak distance, max. valley depth.

Table 5.4 Specifications of the Mitutoyo Surftest 211 device **[29]**

Detecting Method	Inductance
Stylus Material	Diamond
Stylus Tip Radius	5 μm
Measuring Force	4 mN (0.4gF)
Drive Method	One reciprocating
Drive Speed	0.5 mm/s (measuring) Approx. 1 mm/s (returning)
Display	Liquid Crystal
Power Supply	Nickel Cadmium batteries AC Adaptor
Temperature	5 ^{o}C to 40 ^{o}C
Total number of samples taken during measuring	5
Traversing length	Evaluation Length ($\lambda_c \times 5$) + 1 mm.

Parameter	**Measurement Range**	**Cutoff distance λ_c (mm)**	**Length (mm)**	**Traversing Length (mm)**
Ra	0.05 – 40 μm	0.25	1.25	2.25
		0.8	4	5
		2.5	12.5	13.5
*Rmax(DIN) *Rz (DIN)	0.3 – 160 μm	0.25	1.25	2.25
		0.8	4	5
		2.5	12.5	13.5
**Rmax (JIS) **Rz(JIS) (unfiltered)	0.3 – 160 μm	-	0.25	1.25
		-	0.8	1.8
		-	2.5	3.5

**Rz(DIN): Average peak to valley height* **Rmax(DIN): Mximum peak to valley height*

***Rz(JIS): Ten Point Height of Irregularities* ***Rmax(JIS): Maximum height of the profile*

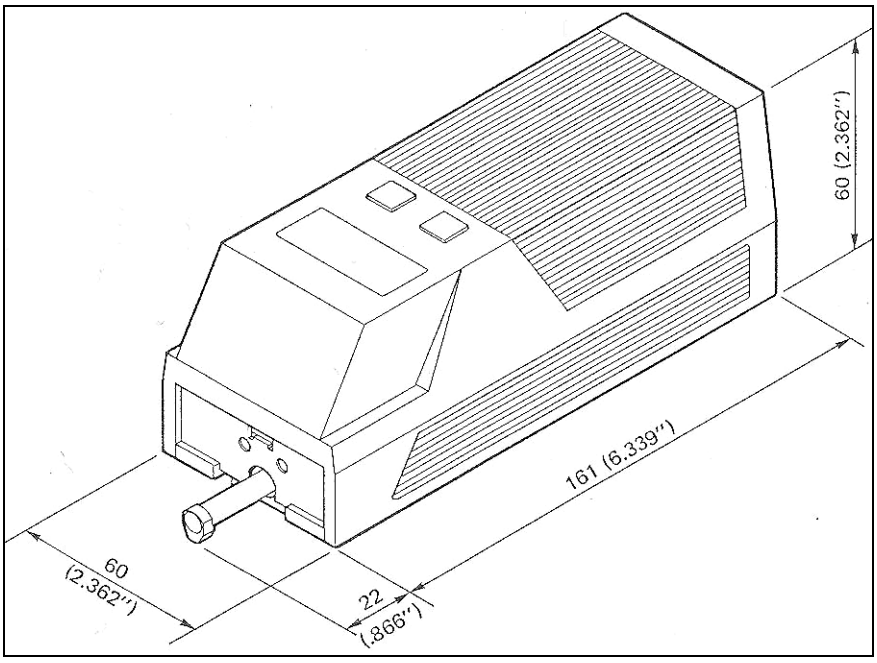


Fig. 5.5 Schematic of Mitutuyo Suftest 211 device

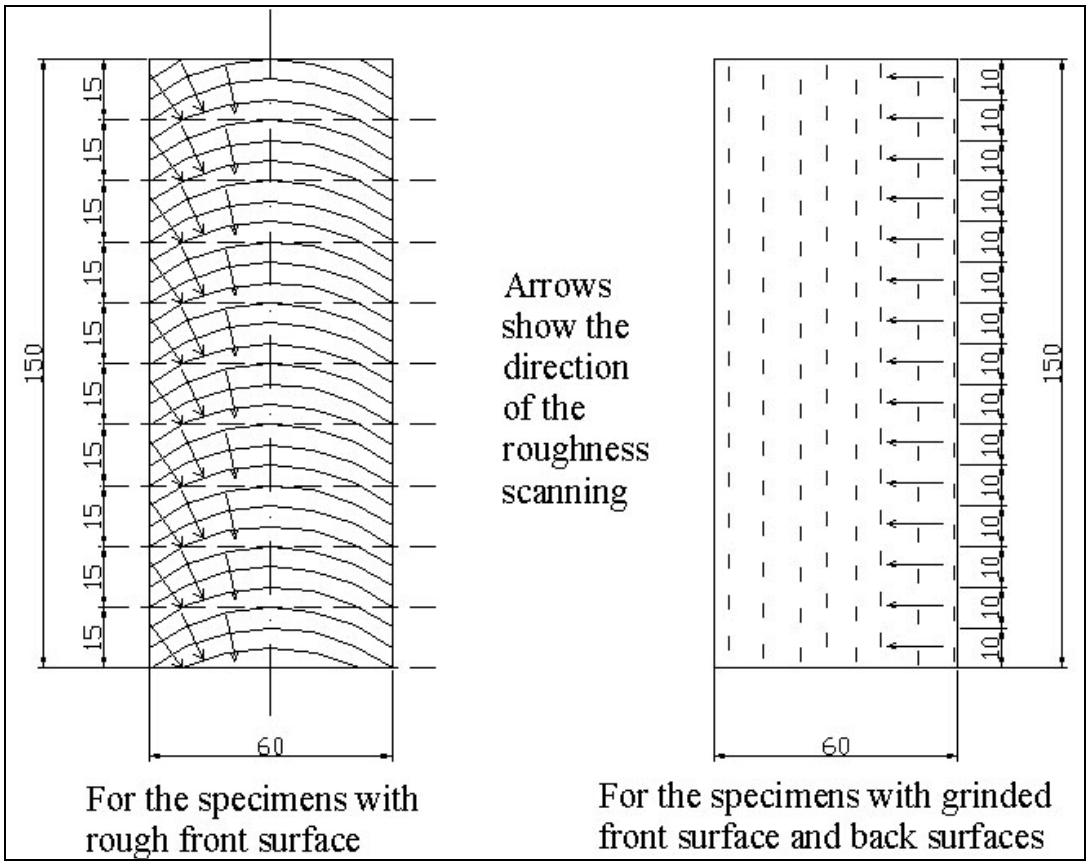


Fig.5.6 Measurement directions

The measurement results of Specimen number 1 to 8 is given in Tables 5.5 to 5.12.

Table 5.5 Roughness Measurement of Specimen 1 & 5 (Front surface)

Measurement Interval (cm)		Roughness (µm Ra)
0	1	0,47
1	2	0,49
2	3	0,46
3	4	0,55
4	5	0,40
5	6	0,43
6	7	0,76
7	8	0,42
8	9	0,42
9	10	0,49
10	11	0,42
11	12	0,42
12	13	0,45
13	14	0,42
14	15	0,40
AVE :		**0,47**
STD. DEV.		**0,09**

Specimen 1

Measurement Interval (cm)		Roughness (µm Ra)
1	2	0,38
2	3	0,39
3	4	0,38
4	5	0,42
5	6	0,39
6	7	0,43
7	8	0,41
8	9	0,38
9	10	0,4
10	11	0,39
11	12	0,42
12	13	0,37
13	14	0,59
14	15	0,48
15	16	0,39
AVE :		**0,41**
STD. DEV.		**0,06**

Specimen 5

Table 5.6 Roughness Measurement of Specimen 2 & 6 (Front surface)

Measurement Interval (cm)		Roughness (µm Ra)	Roughness (µm Ra)	Roughness (µm Ra)
0	1,5	4,54	4,29	5,62
1,5	3	4,56	4,30	4,69
3	4,5	4,50	4,41	5,01
4,5	6	4,38	4,69	4,88
6	7,5	4,26	4,57	5,02
7,5	9	4,37	4,43	4,99
9	10,5	4,64	4,36	4,94
10,5	12	4,31	4,45	4,96
12	13,5	4,37	4,49	4,93
13,5	15	4,27	4,45	4,72
AVE :		**4,61**		**µm Ra**
STD. DEV.		**0,31**		

Specimen 2

Measurement Interval (cm)		Roughness (µm Ra)	Roughness (µm Ra)	Roughness (µm Ra)
0	1,5	4,43	4,53	4,82
1,5	3	4,05	4,44	5,07
3	4,5	4,41	4,61	5,05
4,5	6	4,37	4,48	5,20
6	7,5	4,22	4,23	4,91
7,5	9	4,41	4,24	4,98
9	10,5	4,09	4,18	4,81
10,5	12	4,48	4,30	4,71
12	13,5	4,14	4,10	4,56
13,5	15	4,03	4,12	4,62
AVE :		**4,49**		**µm Ra**
STD. DEV.		**0,33**		

Specimen 6

Table 5.7 Roughness Measurement of Specimen 3 & 7 (Front surface)

Measurement Interval (cm)		Roughness (µm Ra)	Roughness (µm Ra)	Roughness (µm Ra)
0	1,5	9,11	10,61	12,46
1,5	3	9,34	10,97	12,14
3	4,5	9,86	10,66	12,98
4,5	6	9,03	11,24	12,50
6	7,5	9,40	11,17	12,42
7,5	9	9,53	11,36	12,68
9	10,5	9,46	11,06	12,27
10,5	12	9,41	11,45	12,72
12	13,5	9,37	11,45	12,35
13,5	15	9,51	11,54	12,46
AVE :		**11,02**		**µm Ra**
STD. DEV.		**1,32**		

Specimen 3

Measurement Interval (cm)		Roughness (µm Ra)	Roughness (µm Ra)	Roughness (µm Ra)
0	1,5	9,55	10,80	12,77
1,5	3	9,72	11,42	12,41
3	4,5	9,46	11,77	12,79
4,5	6	9,13	11,10	12,19
6	7,5	9,34	11,09	12,36
7,5	9	9,32	11,61	12,89
9	10,5	9,04	11,40	12,86
10,5	12	9,32	11,12	12,47
12	13,5	9,36	11,04	12,43
13,5	15	9,65	10,96	12,31
AVE :		**11,06**		**µm Ra**
STD. DEV.		**1,34**		

Specimen 7

Table 5.8 Roughness Measurement of Specimen 4 & 8 (Front surface)

Measurement Interval (cm)		Roughness (µm Ra)	Roughness (µm Ra)	Roughness (µm Ra)
0	1,5	26,80	27,24	26,61
1,5	3	28,30	27,29	26,80
3	4,5	28,03	27,46	26,16
4,5	6	26,17	26,56	25,36
6	7,5	26,70	26,55	25,44
7,5	9	26,31	25,86	25,35
9	10,5	27,47	28,67	25,91
10,5	12	27,48	27,18	26,12
12	13,5	26,43	27,70	25,96
13,5	15	27,40	25,66	25,73
AVE :		**26,69**		**µm Ra**
STD. DEV.		**0,88**		

Specimen 4

Measurement Interval (cm)		Roughness (µm Ra)	Roughness (µm Ra)	Roughness (µm Ra)
0	1,5	27,16	26,55	26,38
1,5	3	28,19	27,34	26,31
3	4,5	28,13	26,64	25,05
4,5	6	26,21	26,84	26,01
6	7,5	26,63	25,74	25,63
7,5	9	27,11	25,84	26,45
9	10,5	26,46	26,89	25,24
10,5	12	26,69	25,98	26,80
12	13,5	26,43	26,86	26,31
13,5	15	26,35	26,50	25,88
AVE :		**26,49**		**µm Ra**
STD. DEV.		**0,70**		

Specimen 8

Back Surface Measurements

Table 5.9 Roughness Measurement of Specimen 1 & 5 (Back surface)

Measurement Interval (cm)		Roughness (µm Ra)
0	1	2,29
1	2	1,81
2	3	1,46
3	4	1,74
4	5	1,69
5	6	1,59
6	7	1,82
7	8	1,83
8	9	1,76
9	10	1,81
10	11	1,67
11	12	1,93
12	13	1,84
13	14	1,66
14	15	1,76
AVE :		**1,78**
STD. DEV.		**0,18**

Specimen 1

Measurement Interval (cm)		Roughness (µm Ra)
1	2	1,60
2	3	1,81
3	4	1,85
4	5	1,57
5	6	1,61
6	7	1,56
7	8	1,49
8	9	1,62
9	10	1,66
10	11	1,56
11	12	1,41
12	13	1,41
13	14	1,48
14	15	1,45
15	16	1,65
AVE :		**1,58**
STD. DEV.		**0,13**

Specimen 5

Table 5.10 Roughness Measurement of Specimen 2 & 6 (Back surface)

Measurement Interval (cm)		Roughness (µm Ra)
0	1	2,04
1	2	1,78
2	3	2,01
3	4	1,78
4	5	1,61
5	6	1,71
6	7	1,65
7	8	1,60
8	9	1,61
9	10	1,74
10	11	1,96
11	12	1,88
12	13	1,64
13	14	1,35
14	15	1,62
AVE :		**1,73**
STD. DEV.		**0,18**

Specimen 2

Measurement Interval (cm)		Roughness (µm Ra)
1	2	1,82
2	3	1,94
3	4	1,74
4	5	1,63
5	6	1,67
6	7	1,7
7	8	1,81
8	9	1,81
9	10	1,72
10	11	1,95
11	12	1,6
12	13	1,58
13	14	1,56
14	15	1,38
15	16	1,68
AVE :		**1,71**
STD. DEV.		**0,15**

Specimen 6

Table 5.11 Roughness Measurement of Specimen 3 & 7 (Back surface)

Measurement Interval (cm)		Roughness (µm Ra)
0	1	1,63
1	2	1,78
2	3	1,57
3	4	1,70
4	5	1,45
5	6	1,82
6	7	1,61
7	8	1,68
8	9	1,77
9	10	1,53
10	11	1,97
11	12	1,87
12	13	1,80
13	14	1,60
14	15	1,78
AVE :		**1,70**
STD. DEV.		**0,14**

Specimen 3

Measurement Interval (cm)		Roughness (µm Ra)
1	2	1,32
2	3	1,52
3	4	1,56
4	5	1,70
5	6	1,52
6	7	1,65
7	8	1,97
8	9	1,9
9	10	1,85
10	11	1,88
11	12	1,74
12	13	1,83
13	14	1,86
14	15	1,59
15	16	1,59
AVE :		**1,70**
STD. DEV.		**0,18**

Specimen 7

Table 5.12 Roughness Measurement of Specimen 3 & 7 (Back surface)

Measurement Interval (cm)		Roughness (µm Ra)
0	1	1,80
1	2	1,75
2	3	1,67
3	4	1,69
4	5	1,71
5	6	1,53
6	7	1,86
7	8	1,76
8	9	1,54
9	10	1,65
10	11	1,76
11	12	1,52
12	13	2,01
13	14	1,92
14	15	1,34
AVE :		**1,70**
STD. DEV.		**0,17**

Specimen 4

Measurement Interval (cm)		Roughness (µm Ra)
1	2	1,60
2	3	1,25
3	4	1,62
4	5	1,76
5	6	1,76
6	7	1,83
7	8	1,74
8	9	1,77
9	10	1,67
10	11	1,63
11	12	1,54
12	13	1,72
13	14	1,79
14	15	1,52
15	16	1,73
AVE :		**1,66**
STD. DEV.		**0,15**

Specimen 8

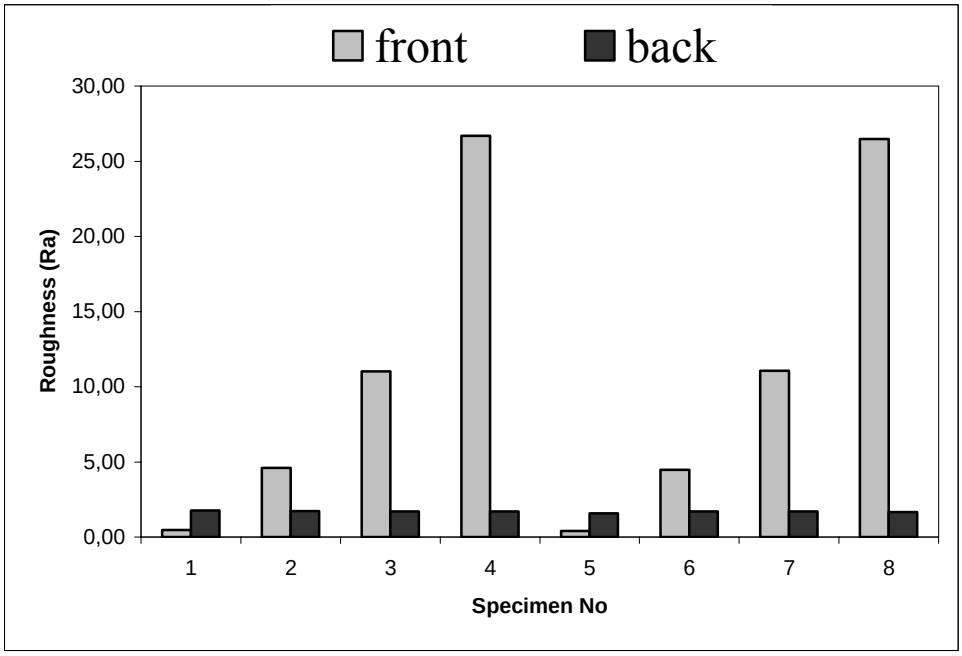


Fig.5.7 Roughness plot of the specimens

To make expressing roughness values easier, from now on Roughness values are round up to 0.5, 4.5, 11, 26.5 µm Ra for the front surfaces and 1.5 µm Ra for the back surfaces.

The following figures show the photos taken from specimen 2-3-4 (4.5, 11, 26.5 µm Ra) to fully describe the surface on which test was done. The maximum valley depth "Pt" and mean roughness depth "Rz" were measured also with Taylor Hobson Form Stylus Series 2 (PGI) device at Bosch-Bursa and result with filtered profiles were graphed by this device.

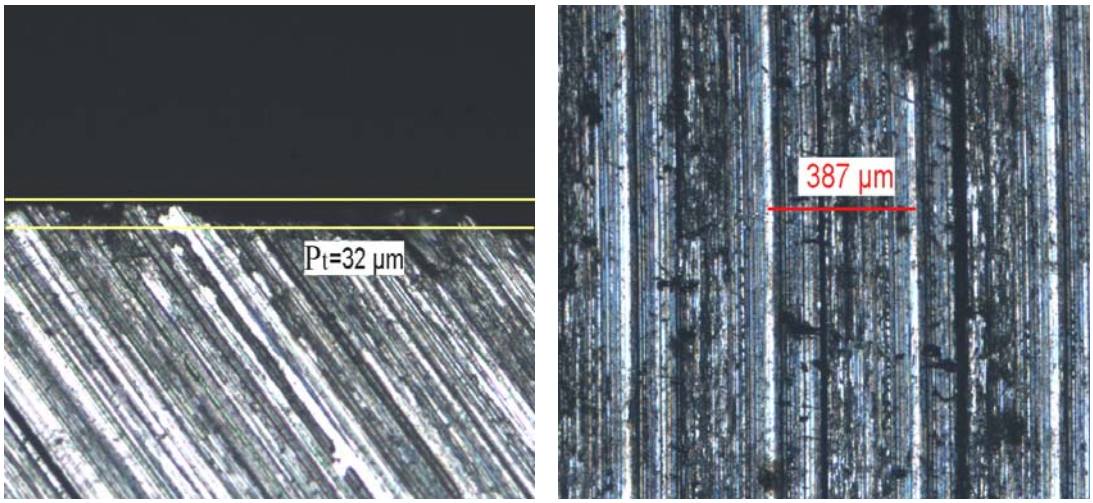


Fig. 5.8 Wavelength and valley depth measurements from specimen 2 (100X magnification)

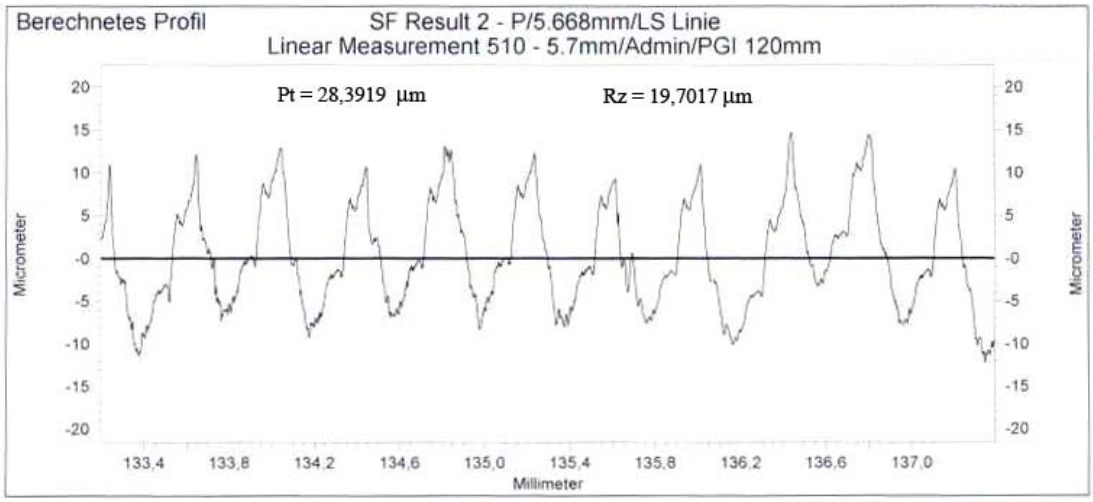


Fig.5.9 Pt, Rz measurements from Taylor Hobson device on Specimen 2

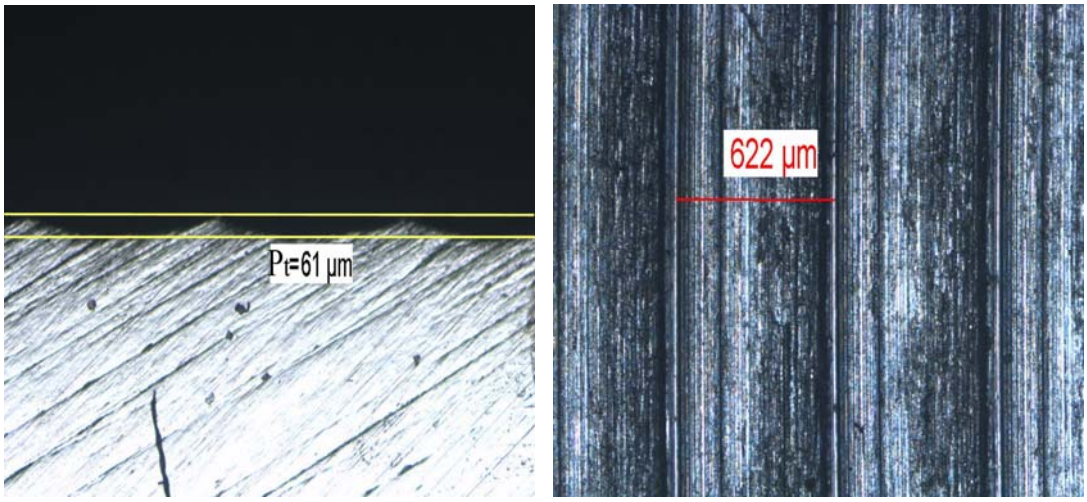


Fig. 5.10 Wavelength and valley depth measurements from specimen 3 (50X magnification)

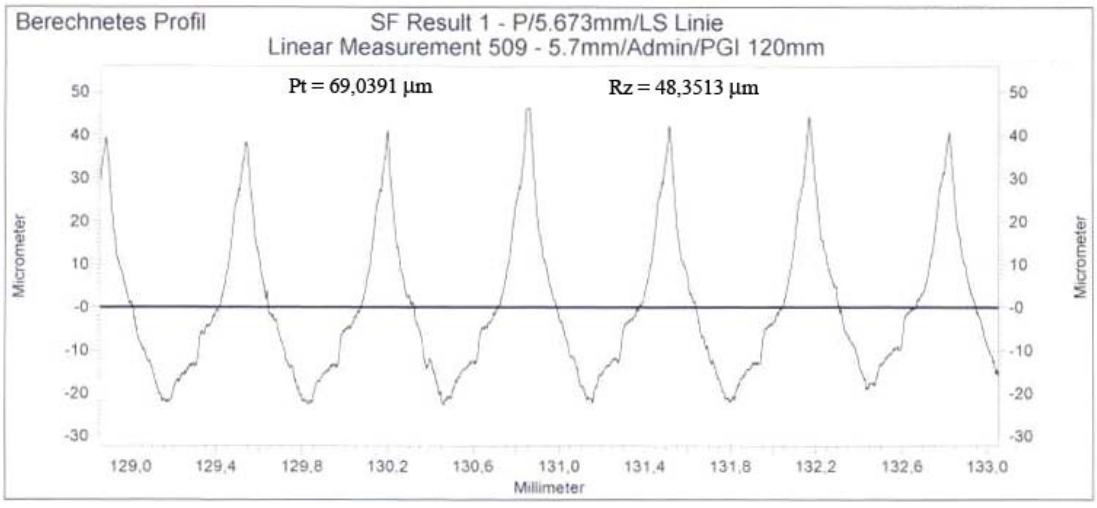


Fig.5.11 Pt, Rz measurements from Taylor Hobson device on Specimen 3

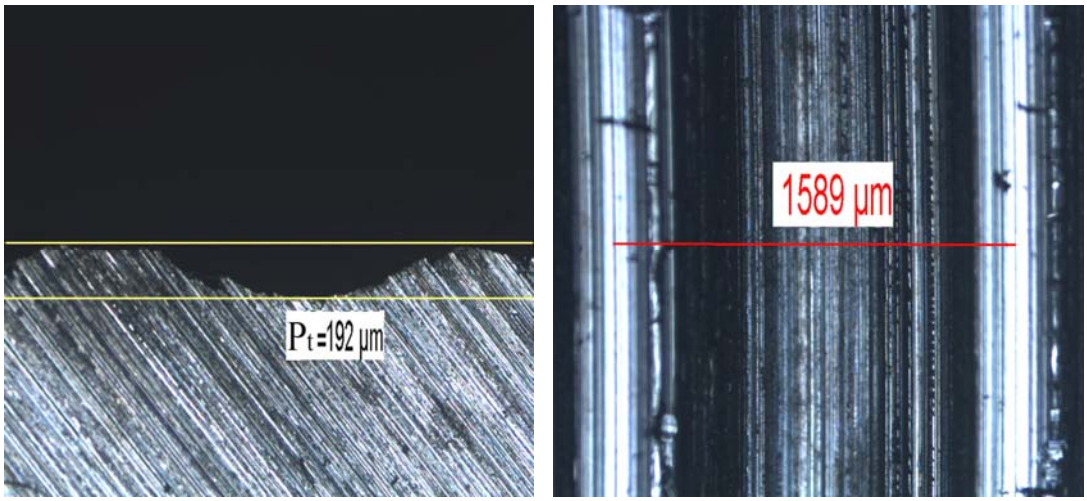


Fig. 5.12 Wavelength and valley depth measurements from specimen 4 (50X magnification)

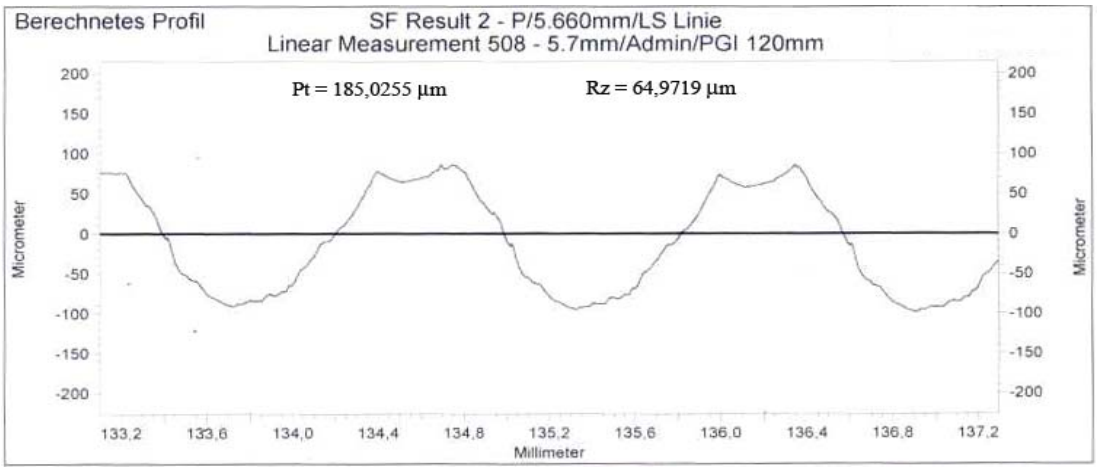


Fig.5.13 Pt, Rz measurements from Taylor Hobson device on Specimen 4

Side Drilled Holes

Holes were drilled to one side of each specimen with CNC Turning Center at M.E.T.U. CAD/CAM Center. A CNC machine was used for drilling the holes because manual drilling may lead some errors while locating the holes to their exact places. CNC machine gave more precise hole locating capability depending on our requirements. Diameters of holes are 1.5, 2, 3, 4 mm. These diameter values were chosen because 1.5 mm. is half of 3 mm. and 2 mm. is half of 4 mm. So a relation may be concluded when the diameters of the holes are doubled while surface quality is varied. The depth of holes through the block was kept constant to 30 mm for each hole, and the holes were drilled at a constant depth of 10.5 mm from the backside (grounded side). Not the centers but the upper quadrant of each hole were located at given depth. The engineering drawing of test specimens is given at APPENDIX B.

The reason of drilling the holes at this depth was because of the transducers near field distances. Different transducers with different frequencies had been used through out tests and it had to be considered that their near field distances will vary with crystal diameter and frequency and should be less than our hole depth. The near field distances of some transducers which METU NDT Center has is given at Table 5.13.

5.2.3 Ultrasonic examination and results

All tests were made by Krautkramer Branson USD 15 ultrasonic testing device belonging to METU NDT Center. 4 different probes were used in the experiments. The critic point of choosing a probe for our test is their near field distances. Near field distances of the probes must be smaller than the depth of the holes (N<48 mm.). Near field distance larger than the depth of holes may lead incorrect results because of the oscillatory behaviour of sound pressure within the near field. The spread angle was another criteria taken into account because it is also possible to have some reflections from other holes which might be confusing. By considering these two parameters, 4 probes were selected which are made by Panametrics with frequencies of 1, 2.25, 3.5, 5 MHz. Information about the probes used (model, serial no, frequency, crystal diameter) are presented in tables.

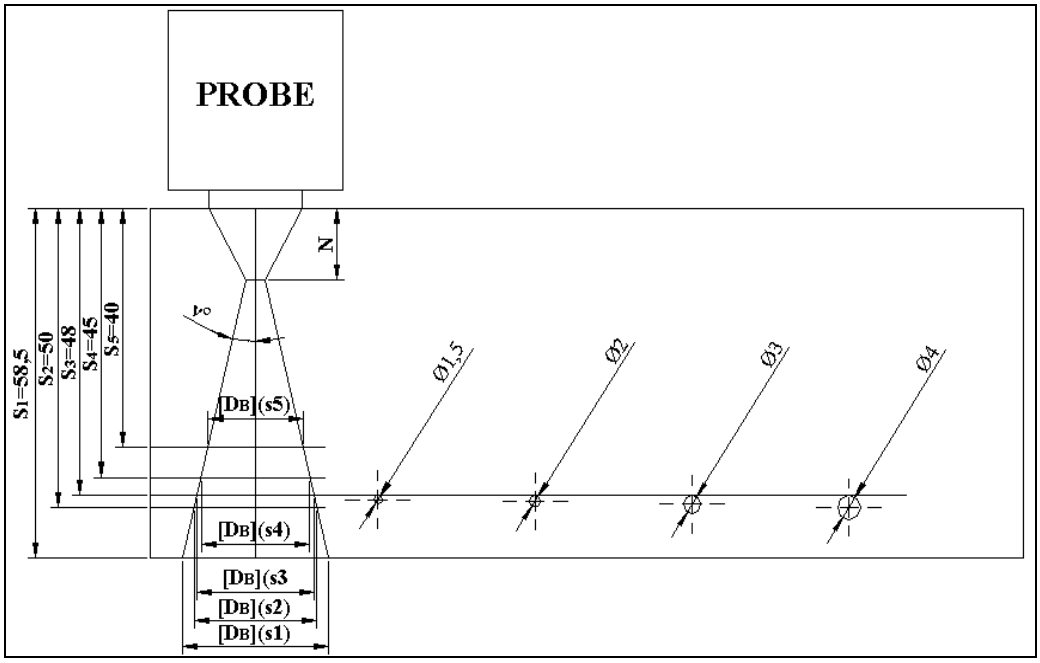


Fig. 5.14: Schematic of beam spread in specimen

Table 5.13: Sound beam and beam spread specifications of some different probes

Frequency, f (MHz)	**1**	**1**	**2**	**2,25**	**2**	**3,5**	**4**	**4**	**5**	**10**
Crystal Dia, D (mm)	24	12,7	12,7	12,7	24	12,7	12,7	24	12,7	12,7
Sound Velocity, c (m/s)	5920	5920	5920	5920	5920	5920	5920	5920	5920	5920
s1 distance (mm.)	58,5	58,5	58,5	58,5	58,5	58,5	58,5	58,5	58,5	58,5
s2 distance (mm.)	50	50	50	50	50	50	50	50	50	50
s3 distance (mm.)	48	48	48	48	48	48	48	48	48	48
s4 distance (mm.)	45	45	45	45	45	45	45	45	45	45
s5 distance (mm.)	40	40	40	40	40	40	40	40	40	40
Wave Length, λ (mm)	5,92	5,92	2,96	2,63	2,96	1,69	1,48	1,48	1,18	0,59
Near Field, N (mm)	24,32	6,81	13,62	15,33	48,65	23,84	27,24	97,30	34,06	68,11
[DB]-6dB (s1) (mm)	14,43	27,27	13,63	12,12	7,22	7,79	6,82	3,61	5,45	2,73
[DB]-6dB (s2) (mm)	12,33	23,31	11,65	10,36	6,17	6,66	5,83	3,08	4,66	2,33
[DB]-6dB (s3) (mm)	11,84	22,37	11,19	9,94	5,92	6,39	5,59	2,96	4,47	2,24
[DB]-6dB (s4) (mm)	11,10	20,98	10,49	9,32	5,55	5,99	5,24	2,78	4,20	2,10
[DB]-6dB (s5) (mm)	9,87	18,65	9,32	8,29	4,93	5,33	4,66	2,47	3,73	1,86
[DB]-20dB (s1) (mm)	28,86	54,54	27,27	24,24	14,43	15,58	13,63	7,22	10,91	5,45
[DB]-20dB (s2) (mm)	24,67	46,61	23,31	20,72	12,33	13,32	11,65	6,17	9,32	4,66
[DB]-20dB (s3) (mm)	23,68	44,75	22,37	19,89	11,84	12,79	11,19	5,92	8,95	4,47
[DB]-20dB (s4) (mm)	22,20	41,95	20,98	18,65	11,10	11,99	10,49	5,55	8,39	4,20
[DB]-20dB (s5) (mm)	19,73	37,29	18,65	16,57	9,87	10,65	9,32	4,93	7,46	3,73
[v] -6dB (°)	7,08	13,48	6,69	5,95	3,54	3,82	3,34	1,77	2,67	1,34
[v] -20dB (°)	14,28	27,78	13,48	11,96	7,08	7,65	6,69	3,54	5,35	2,67

Two different couplant types, machine oil and grease, were used to see if there is any effect of couplant type on varying surface roughness. The data collected from the ultrasonic instrument were the gain values required to locate the echo height at %80 of the screen height. But it was not always possible to make the screen height exactly equal to %80. The device sensitivity (Krautkramer Branson USD 15) enables us to make change in the gain value with 0.5 dB. This 0.5 dB reduction or increment makes the height of the echo to change nearly about %4 of the screen height. And it is also known from the literature that %2 error is acceptable in ultrasonic examination **[8]**. So the results from %78.5 to %81.5 were accepted. The procedure followed after calibration of the Ultrasonic Device with K1 block is given below.

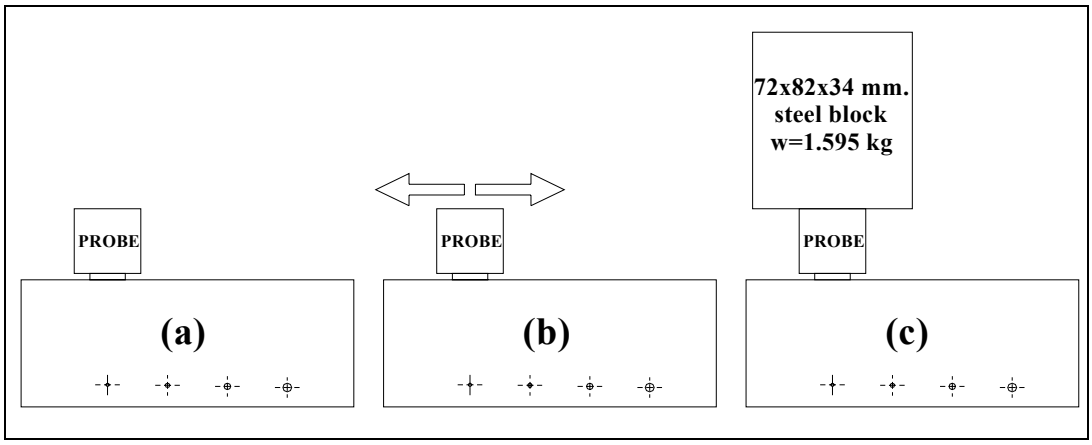


Fig. 5.15: Schematic of steps followed during Ultrasonic Examination

1. First, couplant material is applied to the surface
2. The probe is placed coarsely on the surface to be measured (a)
3. The probe is moved back and forth in order to optimize the echo (b)
4. When maximum echo level is reached, steel block having 1.595 kg weight is put on the probe and waited for equilibrium. (c)
5. After equilibrium, echo height is adjusted to %78.5-81.5 range by changing the gain parameter of the USD 15 ultrasonic device
6. Gain value is recorded
7. Application from 2 to 6 is repeated on the same specimen three times for any inconsistency.
8. Application from 1 to 7 is repeated on the other specimen having the same roughness value.
9. Application from 1 to 8 is repeated on the other specimens having different roughness value.

The results given below are the averages of three measurements as mentioned above, number 7. Used system in tabulating and abbreviation can be described as;

Ref. Specimens 1 & 5 - with roughness 0.5 μm Ra (Average of measurements)

2 Specimens 2 & 6 - with roughness 4.5 μm Ra (Average of measurements)

3 Specimens 3 & 7 - with roughness 11 μm Ra (Average of measurements)

4 Specimens 4 & 8 - with roughness 26.5 μm Ra (Average of measurements)

∅ Crystal diameter of the transducer (in)

Tabulated results for different probe frequencies

Table 5.14 Results from 1 MHz probe, with Machine Oil and Grease as Couplant

Brand:	Panametrics			
Model:	V103			
Serial:	157314			
1 MHz ∅0.5" Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
Backwall	56,5	67,5	81	85
1,5 mm	73,5	83,5	95,5	99
2 mm	72,5	83	95	98,5
3 mm	71	80,5	93,5	97,5
4 mm	69,5	79,5	92	96,5

Brand:	Panametrics			
Model:	V103			
Serial:	157314			
1 MHz ∅0.5" Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
Backwall	63,5	67,5	73,5	80,5
1,5 mm	78,5	83	90,5	97
2 mm	77,5	82,5	89	96
3 mm	76,5	80,5	88	93,5
4 mm	75	79,5	86,5	93

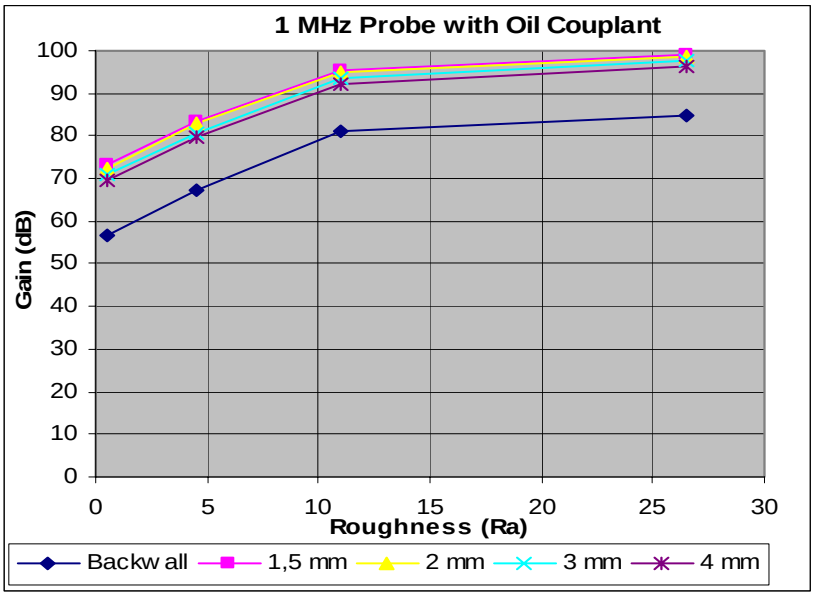


Fig.5.16 Plot of measurement with 1 MHz and machine oil couplant

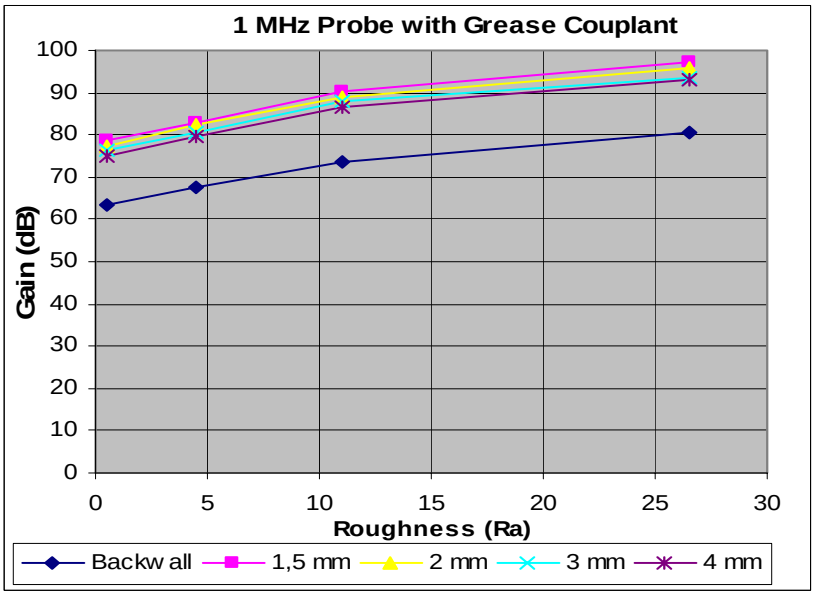


Fig.5.17 Plot of measurement with 1 MHz and grease couplant

Table 5.15 Results from 2,25 MHz probe, with Machine Oil and Grease as Couplant

Brand:	Panametrics			
Model:	V106			
Serial:	147515			
2,25 MHz ∅0.5" Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
Backwall	45,5	57	70,5	74,5
1,5 mm	62	73,5	86,5	90
2 mm	61	73	86	89
3 mm	59	70	84,5	88
4 mm	58	69	82,5	86,5

Brand:	Panametrics			
Model:	V106			
Serial:	147515			
2,25 MHz ∅0.5" Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
Backwall	45,5	53,5	64,5	72
1,5 mm	62	68,5	79,5	87
2 mm	61	67,5	78,5	86,5
3 mm	59,5	66	77	85
4 mm	58	64,5	75,5	83,5

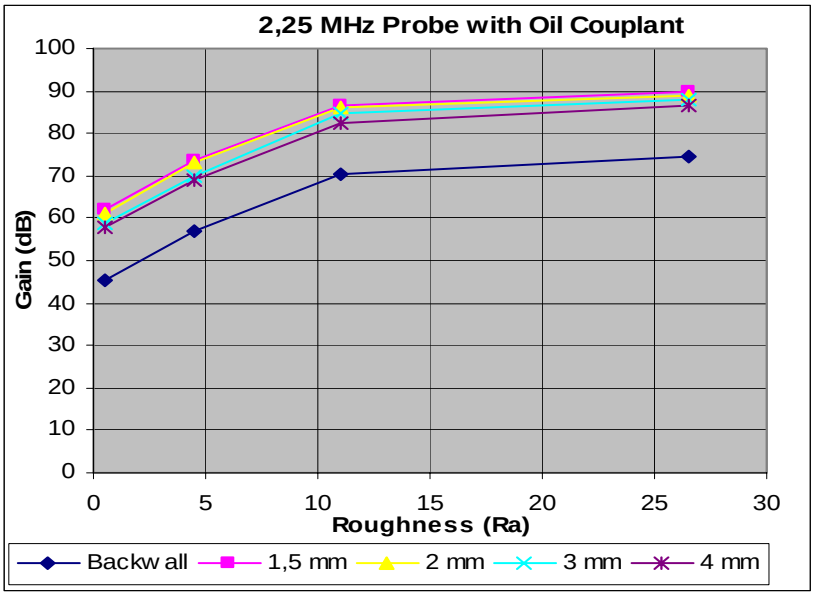


Fig.5.18 Plot of measurement with 2,25 MHz and machine oil couplant

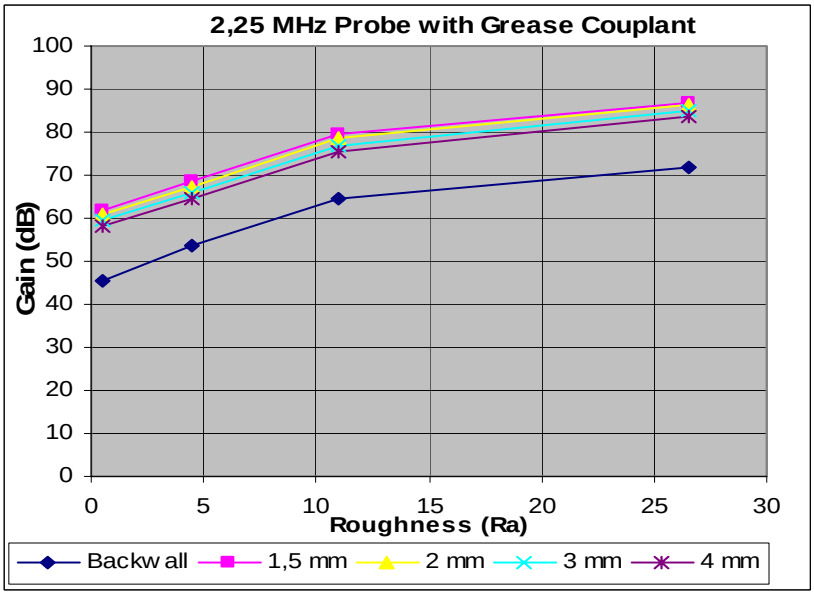


Fig.5.19 Plot of measurement with 2,25 MHz and grease couplant

Table 5.16 Results from 3,5 MHz probe, with Machine Oil and Grease as Couplant

Brand:	Panametrics			
Model:	V182			
Serial:	124312			
3,5 MHz ∅0.5" Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
Backwall	33,5	48,5	62,5	64
1,5 mm	51	64	78,5	81
2 mm	50,5	63,5	77,5	79,5
3 mm	48,5	62	76	78
4 mm	47	61	74	77

Brand:	Panametrics			
Model:	V182			
Serial:	124312			
3,5 MHz ∅0.5" Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
Backwall	34	46	59	61,5
1,5 mm	51,5	61,5	74,5	79
2 mm	50,5	60,5	73,5	78
3 mm	49	59	72	75
4 mm	48	57,5	70,5	74

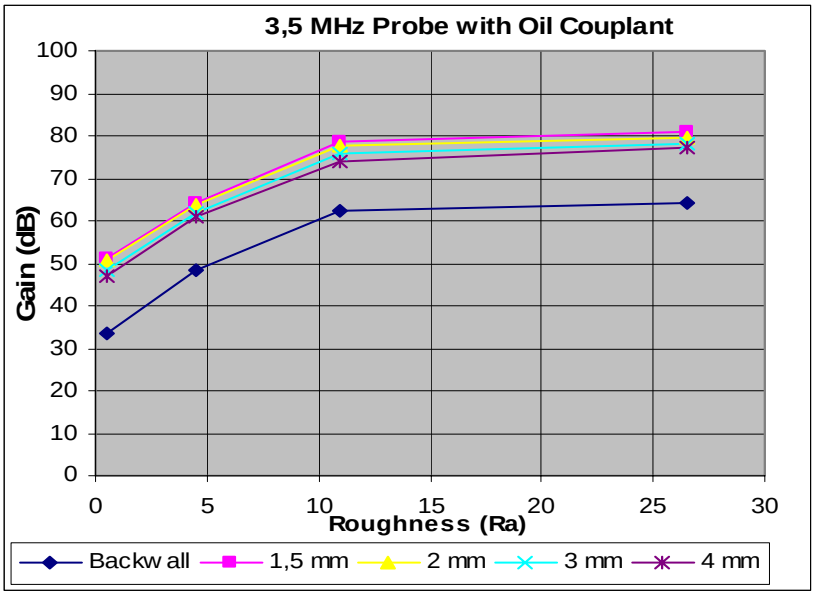


Fig.5.20 Plot of measurement with 3,5 MHz and machine oil couplant

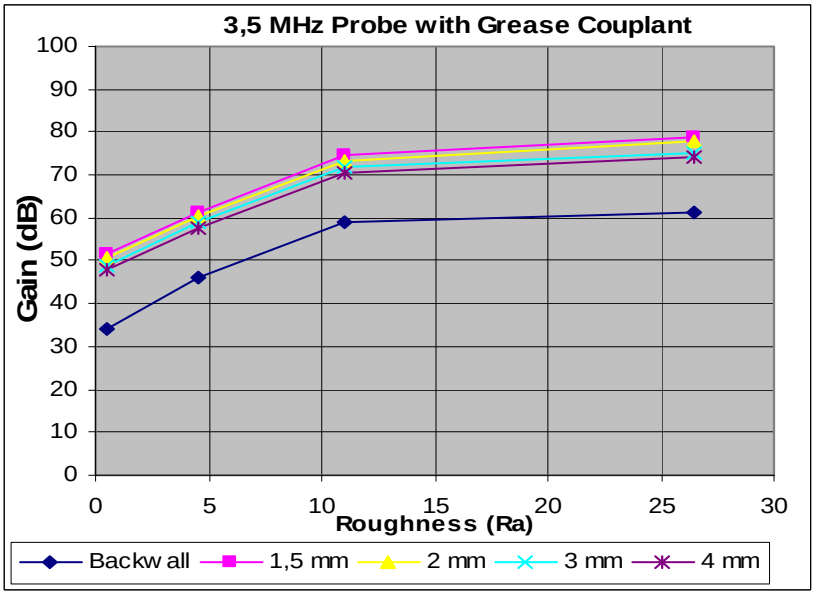


Fig.5.21 Plot of measurement with 3,5 MHz and grease couplant

Table 5.17 Results from 5 MHz probe, with Machine Oil and Grease as Couplant

Brand:	Panametrics			
Model:	V109			
Serial:	149549			
5 MHz ∅0.5" Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
Backwall	31,5	45	58	59,5
1,5 mm	50	61	74	77
2 mm	49	60	73	76
3 mm	47,5	58,5	71,5	74
4 mm	46	57	70	72,5

Brand:	Panametrics			
Model:	V109			
Serial:	149549			
5 MHz ∅0.5" Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
Backwall	31,5	41	54	57,5
1,5 mm	49,5	56,5	70,5	75,5
2 mm	48,5	55,5	69,5	74,5
3 mm	47	54	68	72
4 mm	45,5	52,5	66,5	70,5

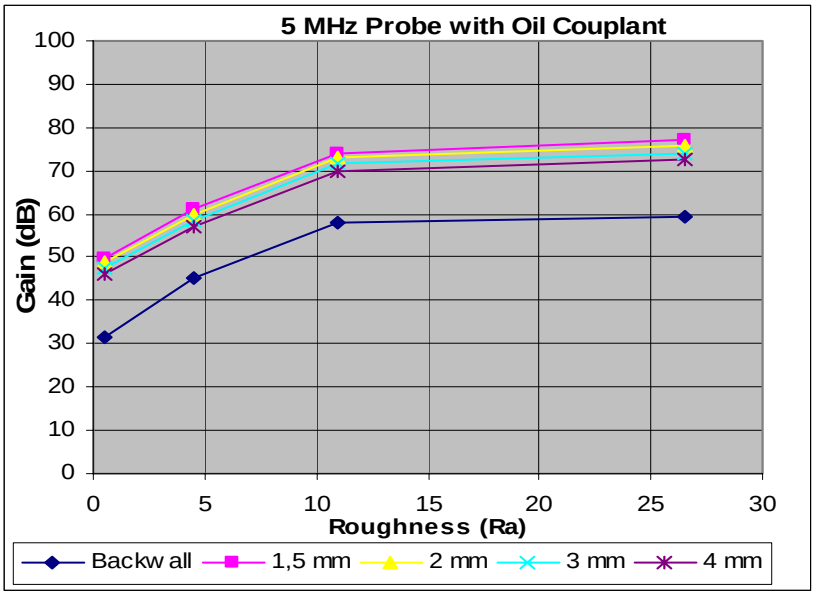


Fig.5.22 Plot of measurement with 5 MHz and machine oil couplant

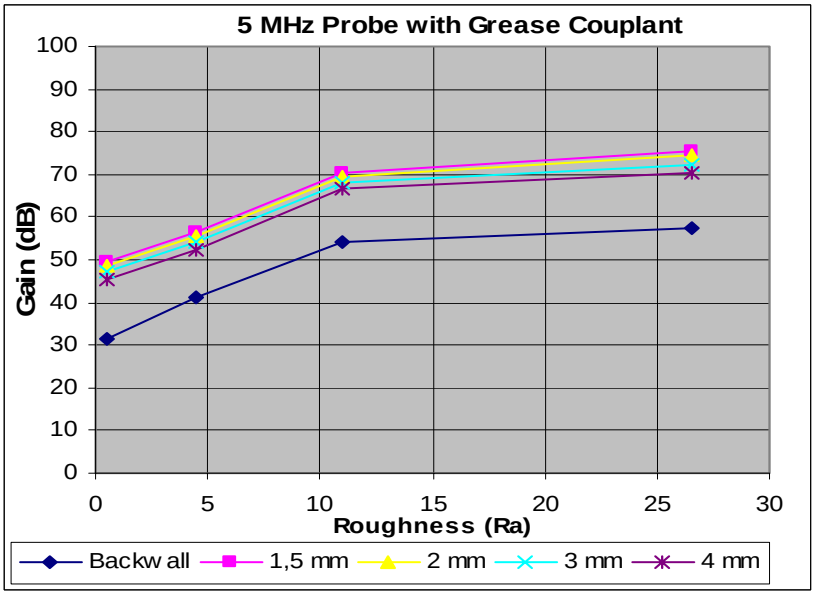


Fig.5.23 Plot of measurement with 3,5 MHz and grease couplant

Plotted Results According to Reflection Point

Table 5.18 Reflection from Backwall with various frequencies, Machine Oil and Grease as Couplant

Backwall Echoes Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	56,5	67,5	81	85
2,25 MHz	45,5	57	70,5	74,5
3,5 MHz	33,5	48,5	62,5	64
5 MHz	31,5	45	58	59,5

Backwall Echoes Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	63,5	67,5	73,5	80,5
2,25 MHz	45,5	53,5	64,5	72
3,5 MHz	34	46	59	61,5
5 MHz	31,5	41	54	57,5

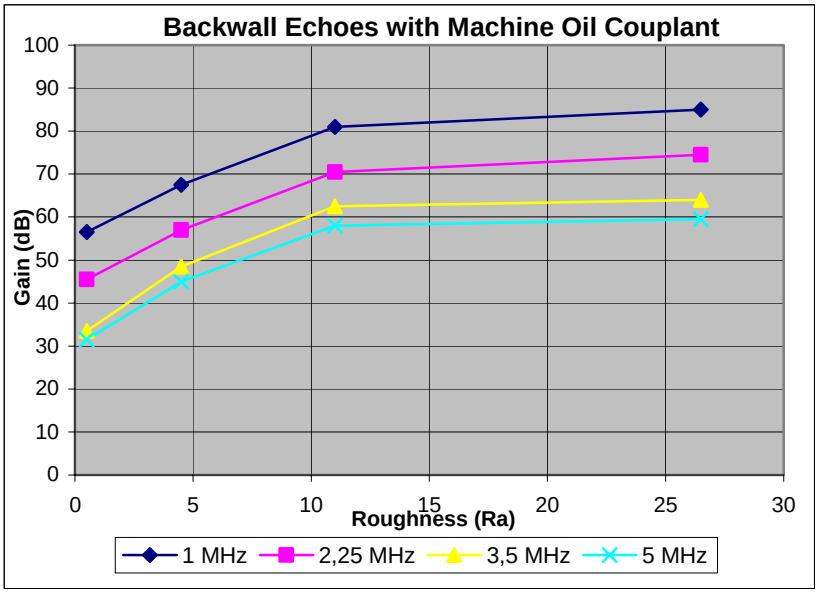


Fig. 5.24 Reflection from backwall with different frequencies(oil)

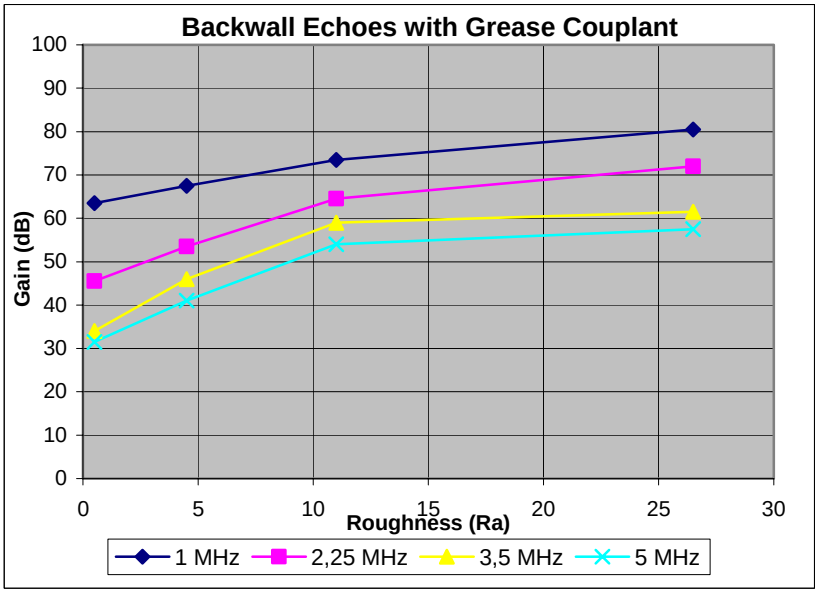


Fig. 5.25 Reflection from backwall with different frequencies(grease)

Table 5.19 Reflection from 1,5mm Hole with various frequencies, Machine Oil and Grease as Couplant

1,5 mm Hole Echoes Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	73,5	83,5	95,5	99
2,25 MHz	62	73,5	86,5	90
3,5 MHz	51	64	78,5	81
5 MHz	50	61	74	77

1,5 mm Hole Echoes Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	78,5	83	90,5	97
2,25 MHz	62	68,5	79,5	87
3,5 MHz	51,5	61,5	74,5	79
5 MHz	49,5	56,5	70,5	75,5

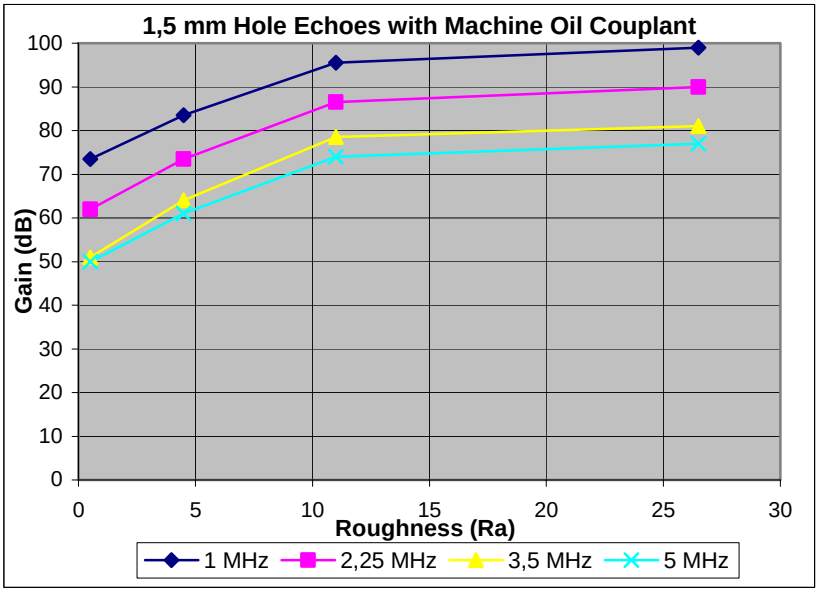


Fig. 5.26 Reflection from 1,5mm. Hole with different frequencies (oil)

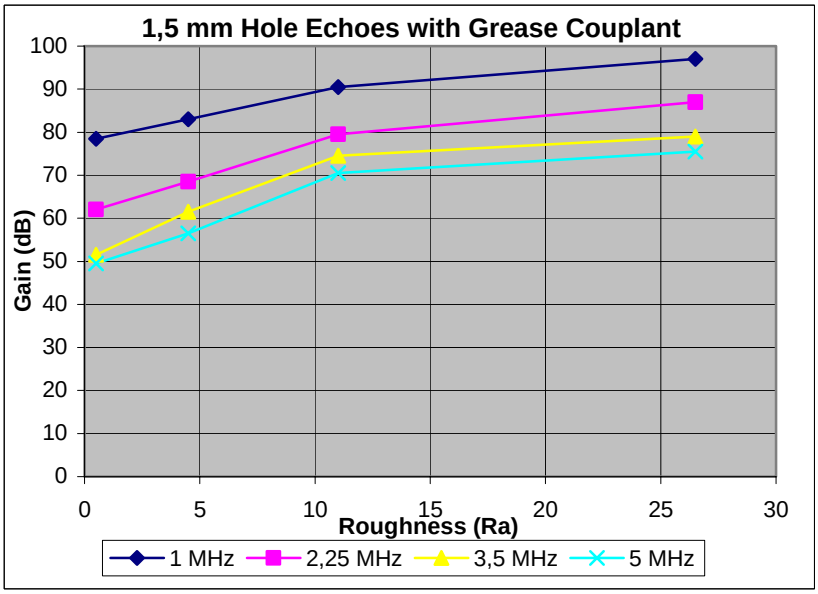


Fig. 5.27 Reflection from 1,5mm. Hole with different frequencies (grease)

Table 5.20 Reflection from 2mm Hole with various frequencies, Machine Oil and Grease as Couplant

2 mm Hole Echoes Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	72,5	83	95	98,5
2,25 MHz	61	73	86	89
3,5 MHz	50,5	63,5	77,5	79,5
5 MHz	49	60	73	76

2 mm Hole Echoes Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	77,5	82,5	89	96
2,25 MHz	61	67,5	78,5	86,5
3,5 MHz	50,5	60,5	73,5	78
5 MHz	48,5	55,5	69,5	74,5

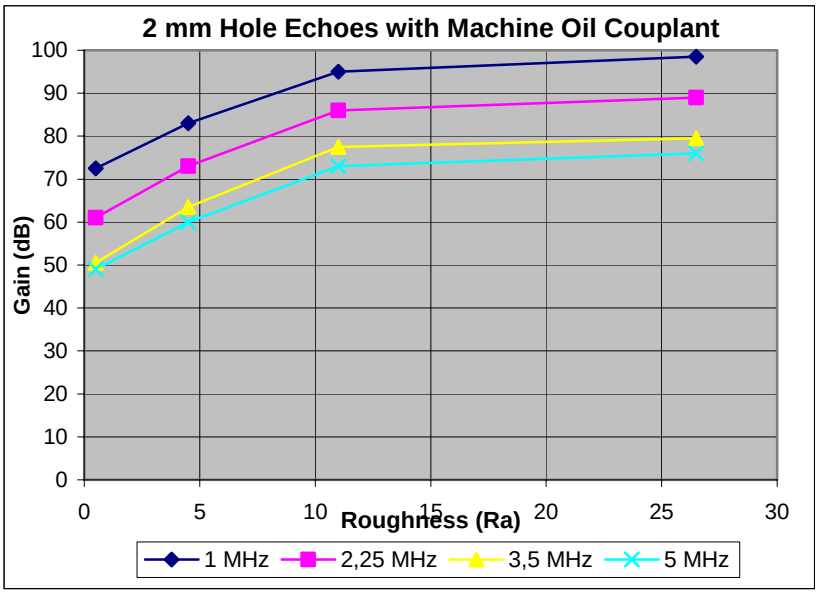


Fig. 5.28 Reflection from 2mm. Hole with different frequencies (oil)

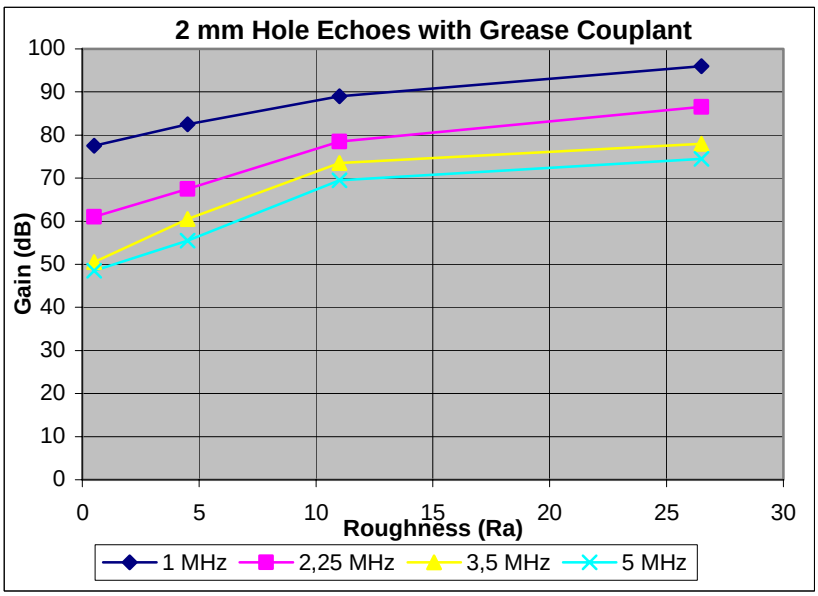


Fig. 5.29 Reflection from 2mm. Hole with different frequencies (grease)

Table 5.21 Reflection from 3mm Hole with various frequencies, Machine Oil and Grease as Couplant

3 mm Hole Echoes Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	71	80,5	93,5	97,5
2,25 MHz	59	70	84,5	88
3,5 MHz	48,5	62	76	78
5 MHz	47,5	58,5	71,5	74

3 mm Hole Echoes Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	76,5	80,5	88	93,5
2,25 MHz	59,5	66	77	85
3,5 MHz	49	59	72	75
5 MHz	47	54	68	72

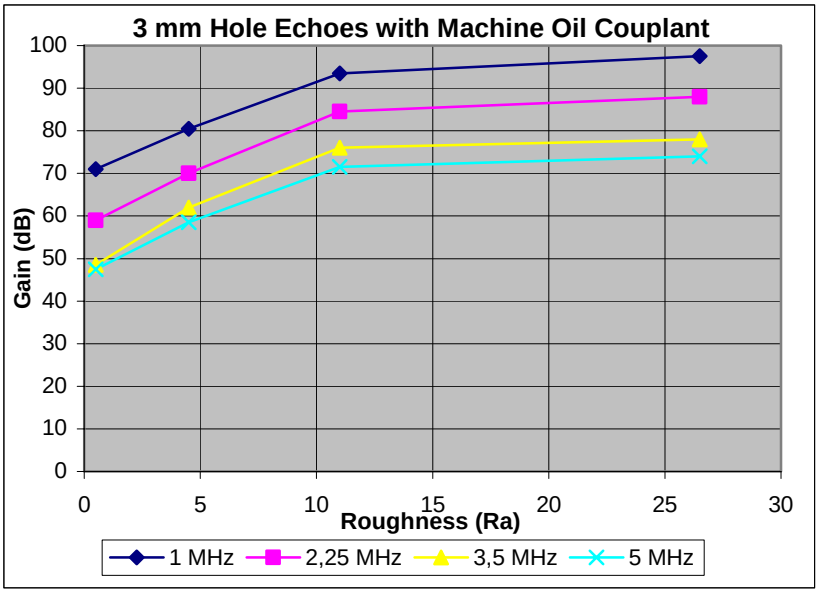


Fig. 5.30 Reflection from 3mm. Hole with different frequencies (oil)

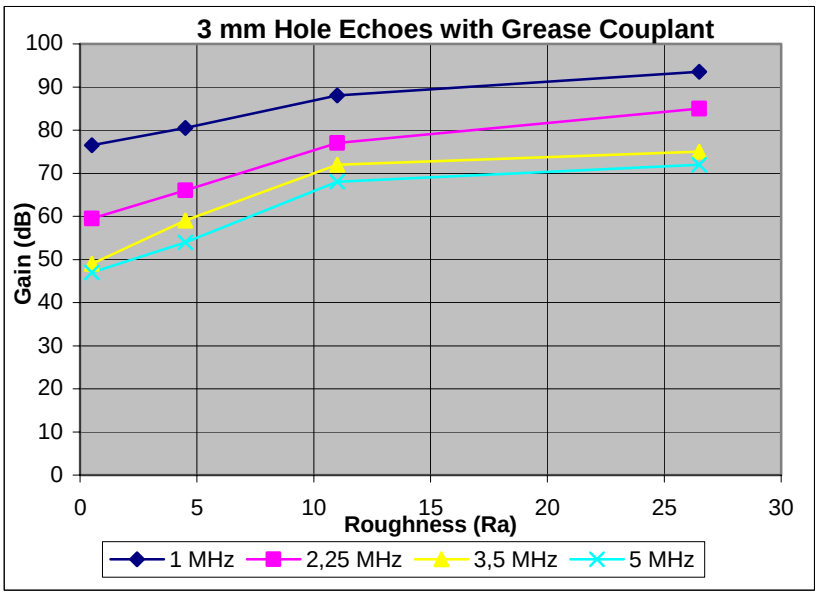


Fig. 5.31 Reflection from 3mm. Hole with different frequencies (grease)

Table 5.22 Reflection from 4mm Hole with various frequencies, Machine Oil and Grease as Couplant

4 mm Hole Echoes Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	69,5	79,5	92	96,5
2,25 MHz	58	69	82,5	86,5
3,5 MHz	47	61	74	77
5 MHz	46	57	70	72,5

4 mm Hole Echoes Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	75	79,5	86,5	93
2,25 MHz	58	64,5	75,5	83,5
3,5 MHz	48	57,5	70,5	74
5 MHz	45,5	52,5	66,5	70,5

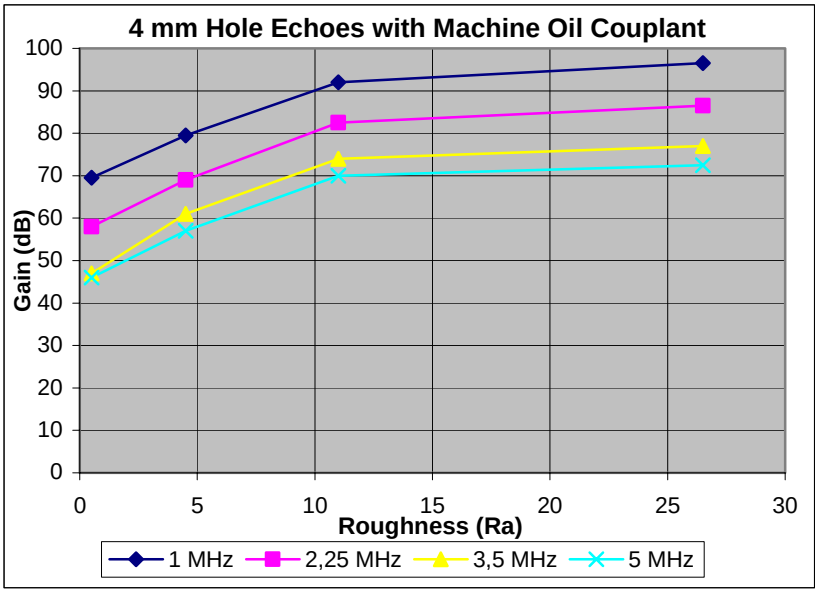


Fig. 5.32 Reflection from 4mm. Hole with different frequencies (oil)

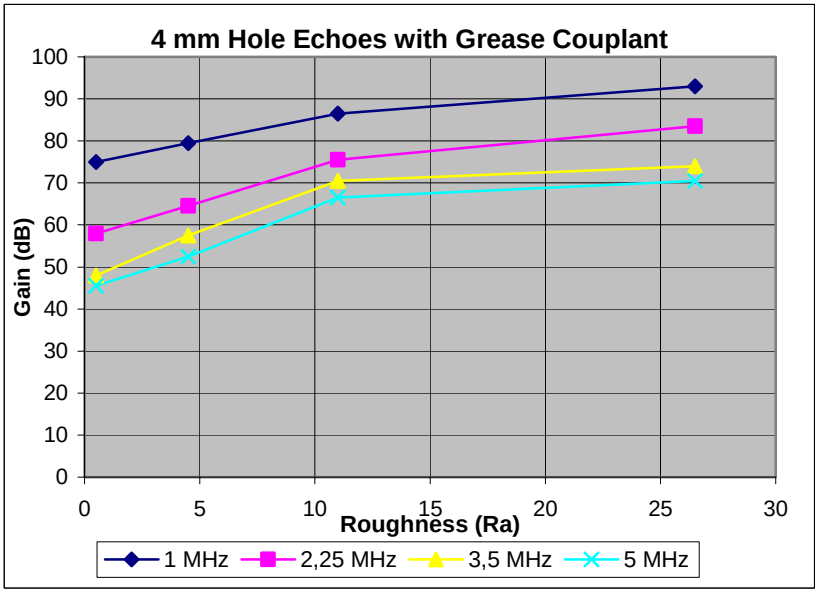


Fig. 5.33 Reflection from 4mm. Hole with different frequencies (grease)

CHAPTER 6

RESULTS AND DISCUSSION

Whether uniform or irregular, a rough surface has a potential of altering ultrasonic testing results. In our case, uniform rough surface obtained by milling operation, it can easily be seen from the experiments that increasing surface roughness decreases the signal amplitude, which is as expected. This means when an ultrasonic sound pressure incidences on a rough boundary of a surface, it looses more of its sound pressure compared with smoother ones. The sound pressure of course not vanishes but scattered out and inside of the material due to roughness. The experiments also showed that there is no directly proportional relation between ultrasonic signal amplitude reduction and increasing surface roughness. In other words, the signal amplitude does not decrease by the same ratio with the increment of surface roughness measured in Ra. This is because, beside increasing sound pressure losses due to roughness, facing with difficulty at coupling of the ultrasonic probe to the testing material is started. When surface has more coarse structure then coupling starts to reduce or fail.

These experiments showed that there is no uncertainty about not being able to detect the discontinuities because of roughness. In every stage of testing and surface condition, reference discontinuities could always be detected. Because of increasing roughness which reduces the sound pressure, more gain was required to bring the echo to 80% of screen height and this caused many unwanted signals started to grow in the ultrasonic screen. These signals could be due to scattered signals from the rough surface or because of the grain structure of the material. But as a result, this may cause a tiny discontinuity to be hard to distinguish from other signals in the screen. This should always be taken in to account when testing with rough surfaces.

To make more points clear, following tables and graphs will be helpful. These tables and graphs are formed by setting the signal amplitude obtained from reference specimen to 100% and then reduction in signal amplitude is calculated by direct proportion for other measurements from rough surfaces.

Table 6.1: % Reduction in gain values with 1 MHz probe

Brand:	Panametrics			
Model:	V103			
Serial:	157314			
1 MHz ∅0.5" Machine Oil Couplant				
GAIN(dB)	**Ref.**	**2**	**3**	**4**
Backwall	100	80,53	56,64	49,56
1,5 mm	100	86,39	70,07	65,31
2 mm	100	85,52	68,97	64,14
3 mm	100	86,62	68,31	62,68
4 mm	100	85,61	67,63	61,15

Brand:	Panametrics			
Model:	V103			
Serial:	157314			
1 MHz ∅0.5" Grease Couplant				
GAIN(dB)	**Ref.**	**2**	**3**	**4**
Backwall	100	93,70	84,25	73,23
1,5 mm	100	94,27	84,71	76,43
2 mm	100	93,55	85,16	76,13
3 mm	100	94,77	84,97	77,78
4 mm	100	94,00	84,67	76,00

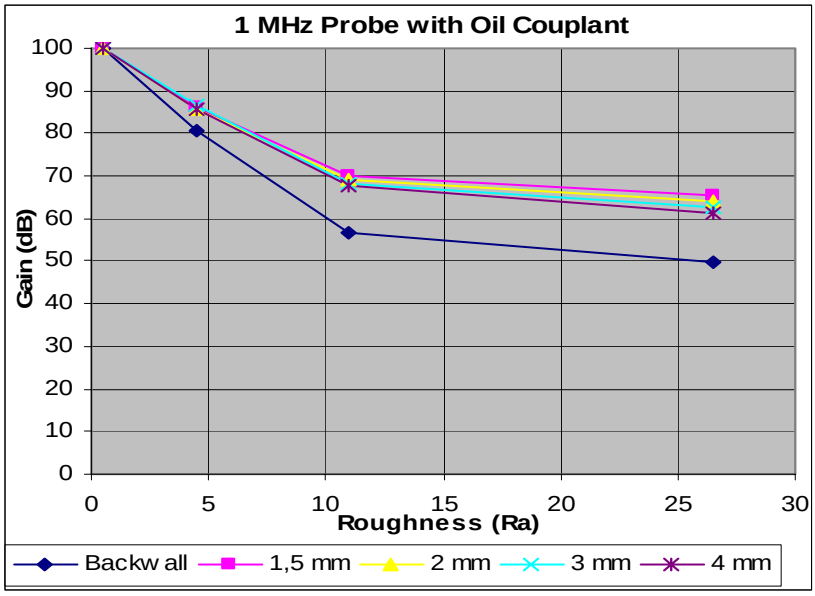


Fig. 6.1: % Reduction graph of 1 MHz probe with oil couplant

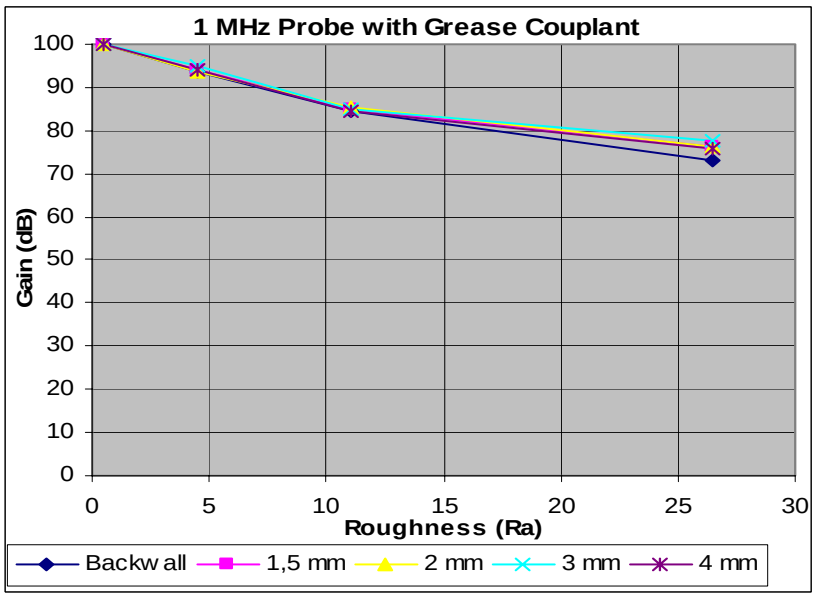


Fig.6.2: % Reduction graph of 1 MHz probe with grease couplant

Table 6.2: % Reduction in gain values with 2.25 MHz probe

Brand:	Panametrics			
Model:	V106			
Serial:	147515			
2,25 MHz Ø0.5" Machine Oil Couplant				
GAIN(dB)	**Ref.**	**2**	**3**	**4**
Backwall	100	74,73	45,05	36,26
1,5 mm	100	81,45	60,48	54,84
2 mm	100	80,33	59,02	54,10
3 mm	100	81,36	56,78	50,85
4 mm	100	81,03	57,76	50,86

Brand:	Panametrics			
Model:	V106			
Serial:	147515			
2,25 MHz Ø0.5" Grease Couplant				
GAIN(dB)	**Ref.**	**2**	**3**	**4**
Backwall	100	82,42	58,24	41,76
1,5 mm	100	89,52	71,77	59,68
2 mm	100	89,34	71,31	58,20
3 mm	100	89,08	70,59	57,14
4 mm	100	88,79	69,83	56,03

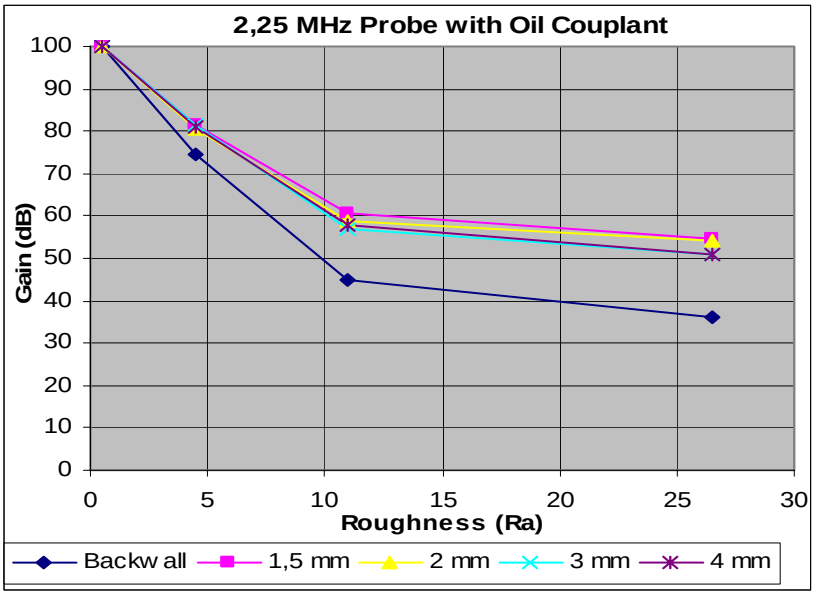


Fig.6.3: % Reduction graph of 2,25 MHz probe with oil couplant

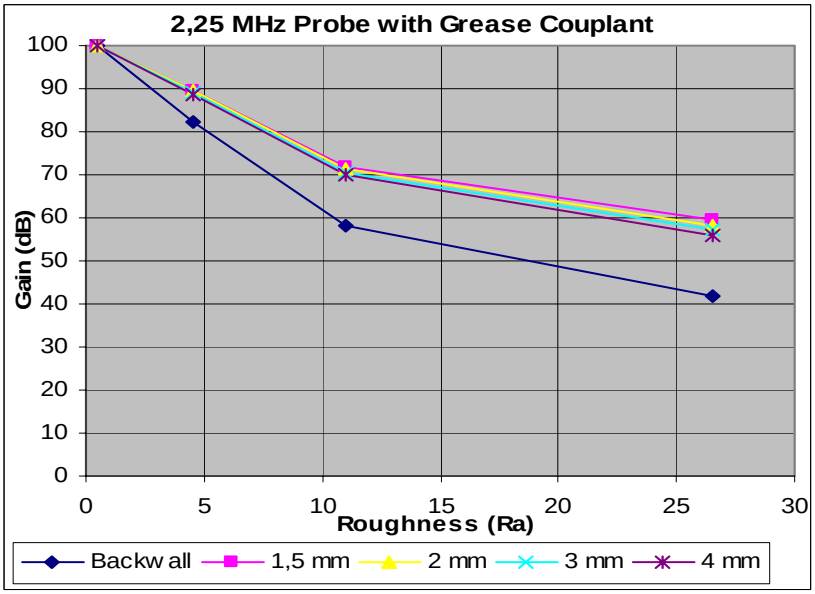


Fig.6.4: % Reduction graph of 2,25 MHz probe with grease couplant

Table 6.3: % Reduction in gain values with 3.5 MHz probe

Brand:	Panametrics			
Model:	V182			
Serial:	124312			
3,5 MHz ∅0.5" Machine Oil Couplant				
GAIN(dB)	**Ref.**	**2**	**3**	**4**
Backwall	100	55,22	13,43	8,96
1,5 mm	100	74,51	46,08	41,18
2 mm	100	74,26	46,53	42,57
3 mm	100	72,16	43,30	39,18
4 mm	100	70,21	42,55	36,17

Brand:	Panametrics			
Model:	V182			
Serial:	124312			
3,5 MHz ∅0.5" Grease Couplant				
GAIN(dB)	**Ref.**	**2**	**3**	**4**
Backwall	100	64,71	26,47	19,12
1,5 mm	100	80,58	55,34	46,60
2 mm	100	80,20	54,46	45,54
3 mm	100	79,59	53,06	46,94
4 mm	100	80,21	53,13	45,83

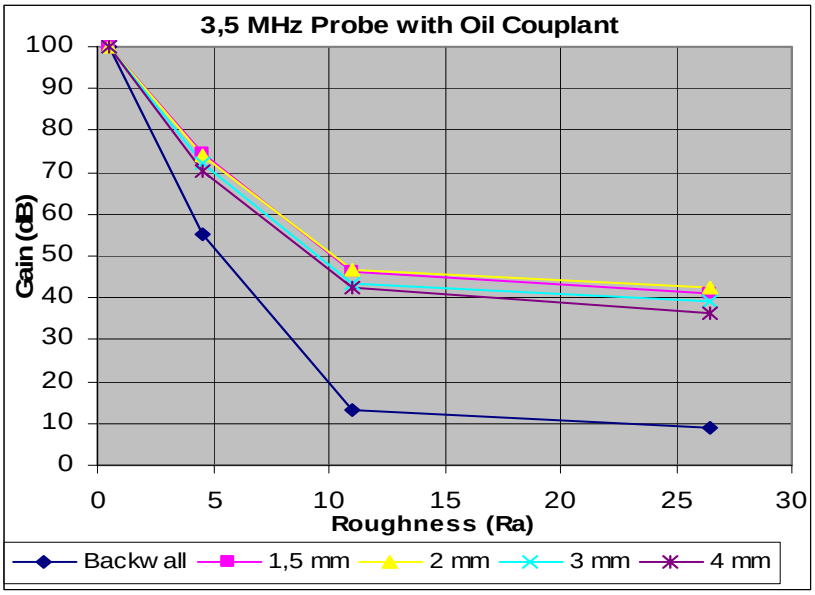


Fig.6.5: % Reduction graph of 3,5 MHz probe with oil couplant

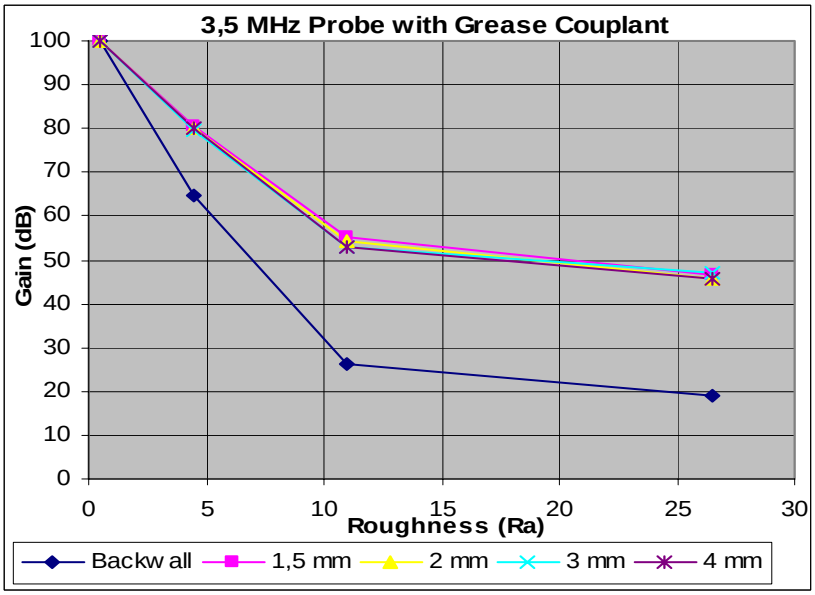


Fig.6.6: % Reduction graph of 3,5 MHz probe with grease couplant

Table 6.4: % Reduction in gain values with 5 MHz probe

Brand:	Panametrics			
Model:	V109			
Serial:	149549			
5 MHz ∅0.5" Machine Oil Couplant				
GAIN(dB)	**Ref.**	**2**	**3**	**4**
Backwall	100	57,14	15,87	11,11
1,5 mm	100	78,00	52,00	46,00
2 mm	100	77,55	51,02	44,90
3 mm	100	76,84	49,47	44,21
4 mm	100	76,09	47,83	42,39

Brand:	Panametrics			
Model:	V109			
Serial:	149549			
5 MHz ∅0.5" Grease Couplant				
GAIN(dB)	**Ref.**	**2**	**3**	**4**
Backwall	100	69,84	28,57	17,46
1,5 mm	100	85,86	57,58	47,47
2 mm	100	85,57	56,70	46,39
3 mm	100	85,11	55,32	46,81
4 mm	100	84,62	53,85	45,05

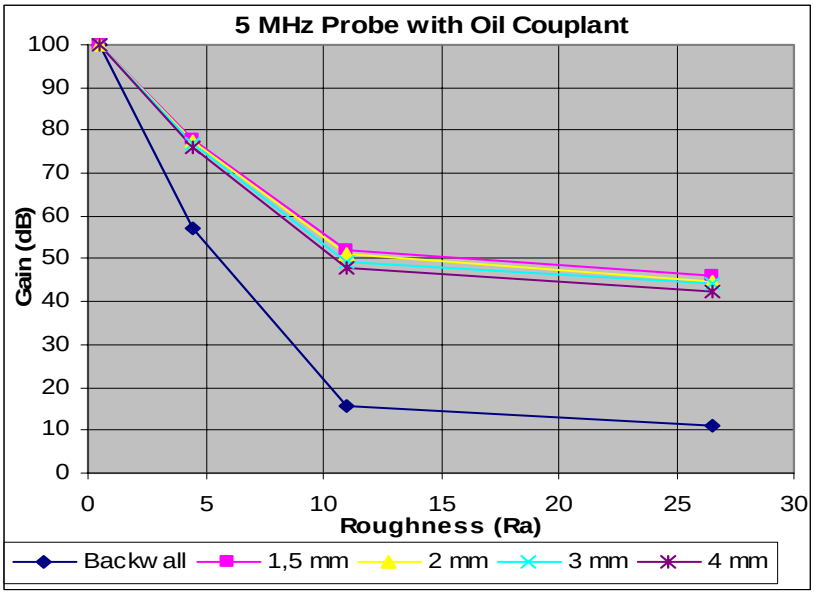


Fig.6.7: % Reduction graph of 5 MHz probe with oil couplant

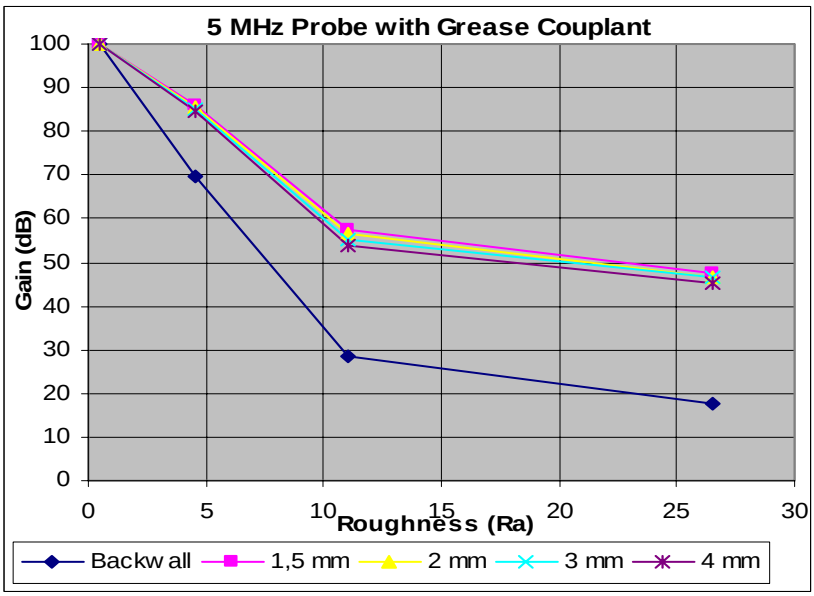


Fig.6.8: % Reduction graph of 5 MHz probe with grease couplant

Plotted Results According to Reflection Point

Table 6.5: % Reduction of backwall echoes with various frequencies

Backwall Echoes Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	100	80,53	56,64	49,56
2,25 MHz	100	74,73	45,05	36,26
3,5 MHz	100	55,22	13,43	8,96
5 MHz	100	57,14	15,87	11,11

Backwall Echoes Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	100	93,70	84,25	73,23
2,25 MHz	100	82,42	58,24	41,76
3,5 MHz	100	64,71	26,47	19,12
5 MHz	100	69,84	28,57	17,46

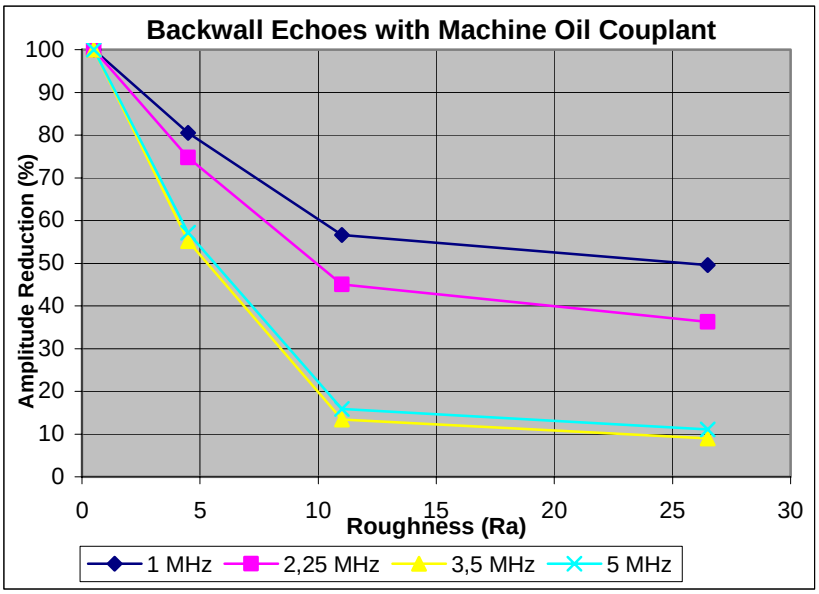


Fig.6.9: % Reduction of backwall echo with oil couplant

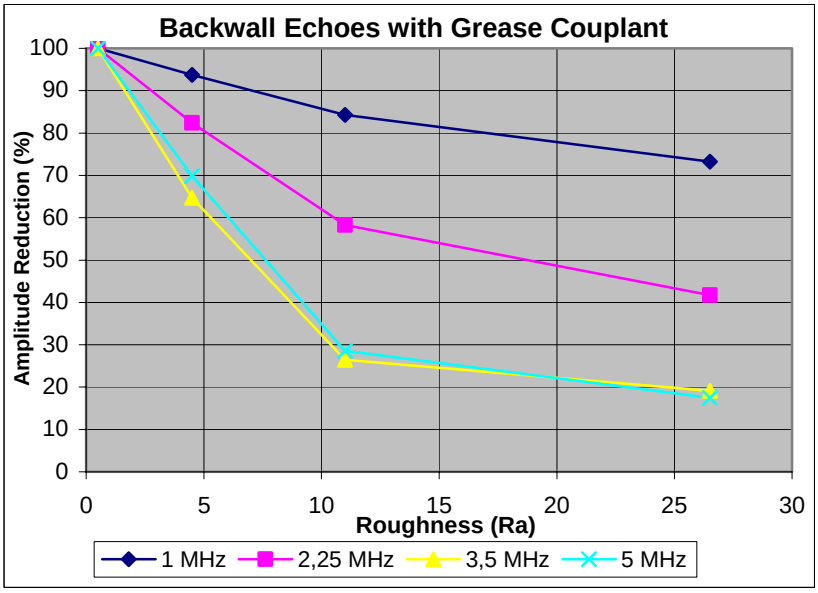


Fig.6.10: % Reduction of backwall echo with grease couplant

Table 6.6: % Reduction of 1,5mm Hole echoes with various frequencies

1,5 mm Hole Echoes Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	100	86,39	70,07	65,31
2,25 MHz	100	81,45	60,48	54,84
3,5 MHz	100	74,51	46,08	41,18
5 MHz	100	78,00	52,00	46,00

1,5 mm Hole Echoes Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	100	94,27	84,71	76,43
2,25 MHz	100	89,52	71,77	59,68
3,5 MHz	100	80,58	55,34	46,60
5 MHz	100	85,86	57,58	47,47

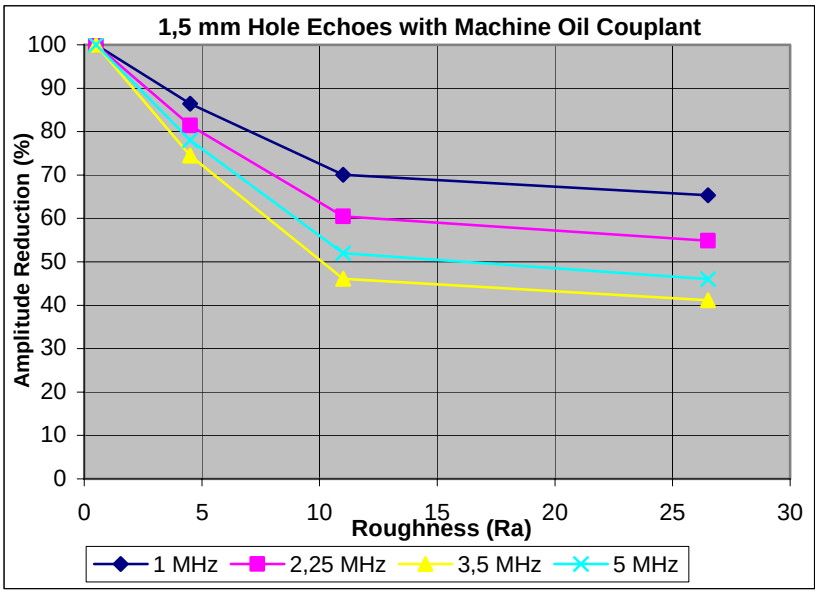


Fig.6.11: % Reduction of 1,5 mm hole echo with oil couplant

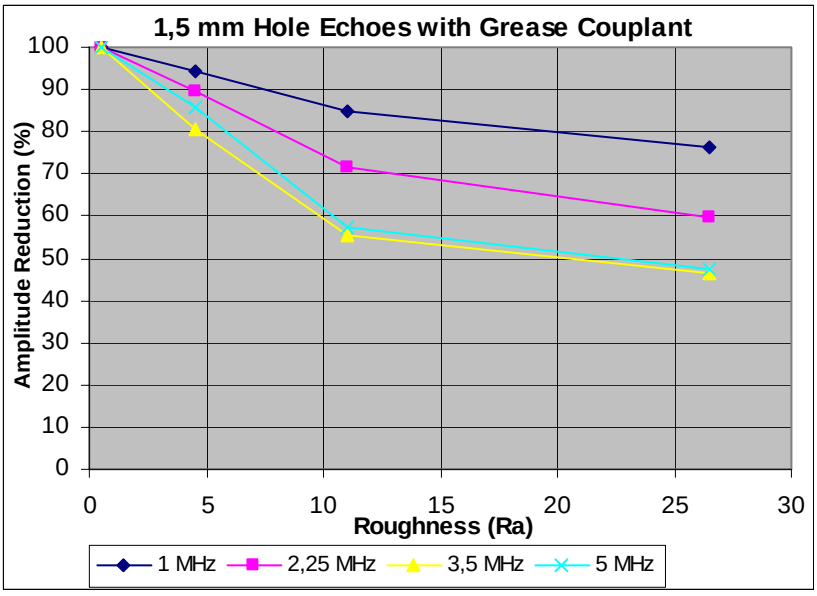


Fig.6.12: % Reduction of 1,5 mm hole echo with grease couplant

Table 6.7: % Reduction of 2mm Hole echoes with various frequencies

2 mm Hole Echoes Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	100	85,52	68,97	64,14
2,25 MHz	100	80,33	59,02	54,10
3,5 MHz	100	74,26	46,53	42,57
5 MHz	100	77,55	51,02	44,90

2 mm Hole Echoes Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	100	93,55	85,16	76,13
2,25 MHz	100	89,34	71,31	58,20
3,5 MHz	100	80,20	54,46	45,54
5 MHz	100	85,57	56,70	46,39

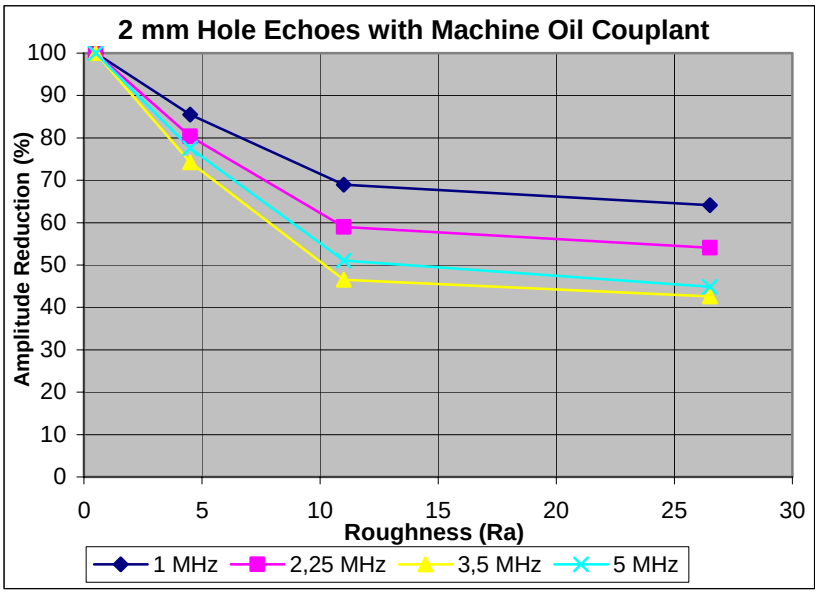


Fig.6.13: % Reduction of 2 mm hole echo with oil couplant

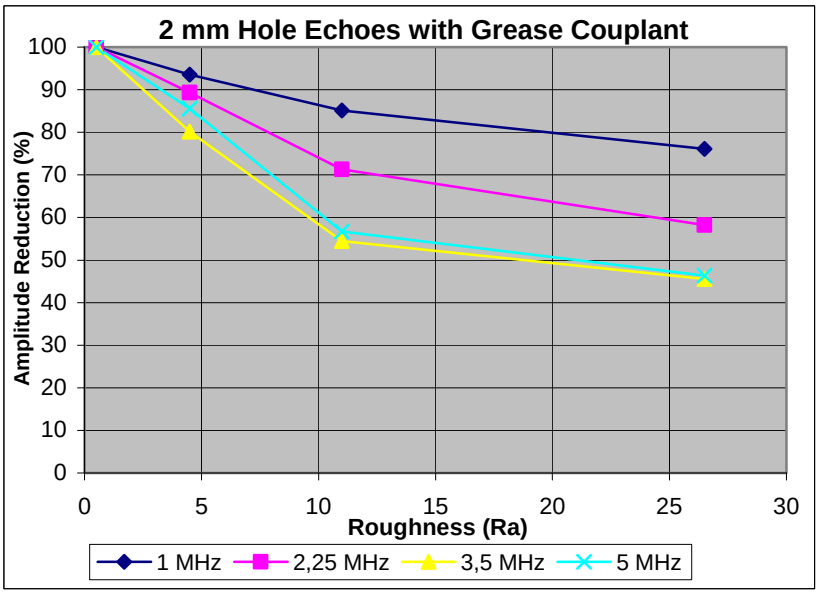


Fig.6.14: % Reduction of 2 mm hole echo with grease couplant

Table 6.8: % Reduction of 3mm Hole echoes with various frequencies

3 mm Hole Echoes Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	100	86,62	68,31	62,68
2,25 MHz	100	81,36	56,78	50,85
3,5 MHz	100	72,16	43,30	39,18
5 MHz	100	76,84	49,47	44,21

3 mm Hole Echoes Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	100	94,77	84,97	77,78
2,25 MHz	100	89,08	70,59	57,14
3,5 MHz	100	79,59	53,06	46,94
5 MHz	100	85,11	55,32	46,81

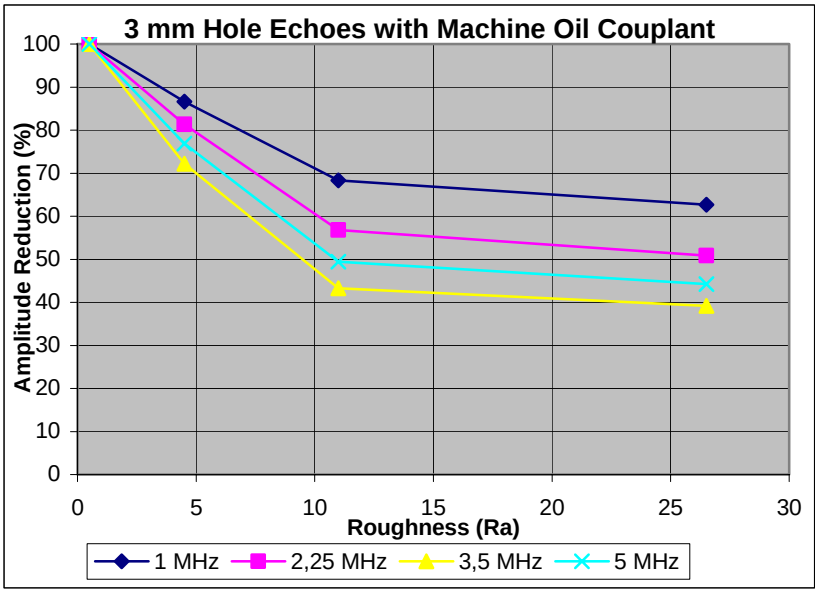


Fig.6.15: % Reduction of 3 mm hole echo with oil couplant

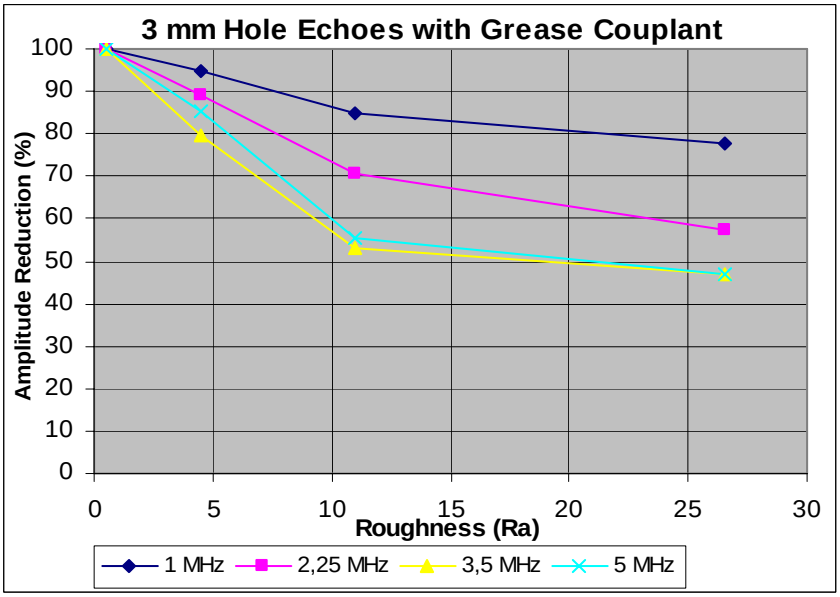


Fig.6.16: % Reduction of 3 mm hole echo with grease couplant

Table 6.9: % Reduction of 4mm Hole echoes with various frequencies

4 mm Hole Echoes Machine Oil Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	100	85,61	67,63	61,15
2,25 MHz	100	81,03	57,76	50,86
3,5 MHz	100	70,21	42,55	36,17
5 MHz	100	76,09	47,83	42,39

4 mm Hole Echoes Grease Couplant				
GAIN (dB)	**Ref.**	**2**	**3**	**4**
1 MHz	100	94,00	84,67	76,00
2,25 MHz	100	88,79	69,83	56,03
3,5 MHz	100	80,21	53,13	45,83
5 MHz	100	84,62	53,85	45,05

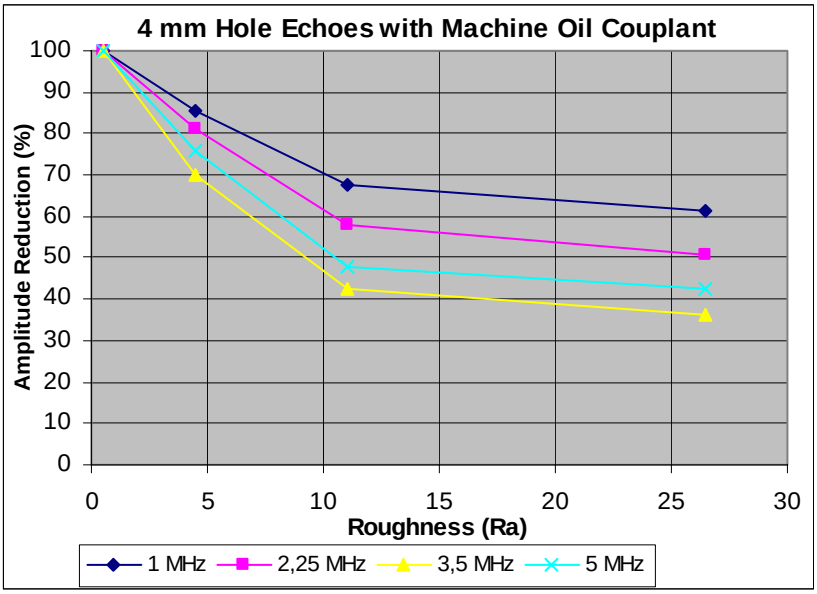


Fig.6.17: % Reduction of 4 mm hole echo with oil couplant

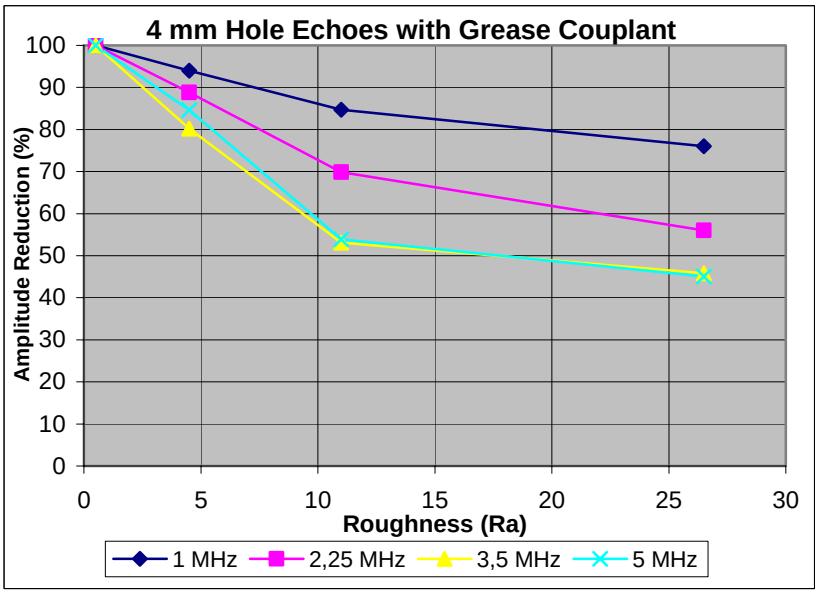


Fig.6.18: % Reduction of 4 mm hole echo with grease couplant

Amplitude reduction tables and graphs give more idea about the phenomena of roughness and ultrasonic signal interface. The reduction in amplitude is lower in low frequency probes. This means when wave length of ultrasonic beam increases, transmission and scattering losses decrease. So choosing a lower frequency probe will give a better result when compared to higher ones. But when using 3.5 MHz and 5 MHz probe situation become just the opposite. Amplitude reduction at 3.5 MHz probe is quite greater that 5 MHz, this is not an expected situation but this should be due to grain structure of specimen material and needs further research. But when testing with any frequency, the reduction behavior of the signal amplitude with roughness was always as exponential decrease. That means the reduction was very high at first, but then the reduction started to get lower although surface roughness continued to increase. This was because of limited coupling of the probe to the samples. When roughness was low, it was possible to couple more surface with ultrasonic probe but when the surface started to get coarse(increasing roughness), only peak points of the surface could be coupled to transmit sound waves and valleys of the surface could not be coupled enough. This limited surface which was formed by peaks of roughness, could not decrease too much because the probe surface must touch some certain amount of surface at the end. So this means, if we have a surface more than 26 μm Ra, the reduction in sound pressure will not be as high as the reduction from 0,5 μm Ra to 10 μm Ra.

These experiments also showed that different couplant usage on rough surfaces has an affect on the signal amplitude values which may be useful in some applications of ultrasonic testing. A significant difference is observed in sound pressure losses. When testing the same specimen with oil and grease, there is more loss at sound pressure if oil couplant is used. (e.g. Table 6.6: when testing a 26.5 μm Ra specimen for 1,5 mm hole with 1 MHz probe, if oil is used, a sound pressure level by 65,31% of its original is obtained, but if grease is used as couplant this level is 76,43%). To generalize this, it can be said that using grease as a couplant reduces losses at sound pressure values which provides us less gain requirement to reach the target. In other words, higher viscosity couplant reduces transmitted wave losses to the specimen when the surface is rough, and requires less gain to reach %80 of screen height which affects ultrasonic device screen to be clear of unwanted signals. On the other

hand, grease couplant usage at highly rough surfaces with higher frequency like 3.5 or 5 MHz may lead some errors. For example if it is intended to examine a piece having 26.5 μm Ra roughness and looking for a 1.5 mm discontinuity (Table 6.6, Fig:6.11-12), it will be get the same amount of original signal level with 3.5 and 5 MHz probes. This will yield to not being able to decide on correct sizing of the discontinuity. But it would not be faced with these type of situations in case oil was used instead.

Ultrasonic inspection can be used to give information about two areas in NDT especially, attenuation measurement and discontinuity detection / sizing. Attenuation measurements find wide application in condition monitoring of materials, as in assessing the microstructural degradation [9]. When measuring attenuation for microstructural characterization, height of reflected amplitude is crucial. In such application, even a small error introduced due to surface roughness could affect and alter the results. But when the case is about sizing the discontinuity, the difference between amplitude values is useful, than Figure 6.1 to 6.8 and Table 6.1 to 6.4 would be useful when testing is made on a component whose roughness is different from the reference component for regular rough milled surfaces. When testing gives same amplitude values for different size of discontinuity, it can be realized that testing with two different probe frequencies will be helpful to decide on the correct size of the discontinuity. (e.g. The same amplitude reduction values for 26.5 μm Ra rough surfaced specimen; Table 6.2, 2.25 MHz with oil couplant, for 3 and 4 mm holes. Table 6.3, 3.5 MHz with grease couplant, for 1.5 and 3 mm holes - Table 6.4, 5 MHz with oil couplant, for 2 and 3 mm holes).

CHAPTER 7

CONCLUSION

The surface condition is an important measure that has to be taken into account when an ultrasonic testing should be done. When it is impractical or uneconomical to prepare the surface to a required condition, the results from these tests can be used as a guide line for better evaluating the results. Some main points concluded from this study can be listed as follows:

- Increasing surface roughness decreases transmitted sound pressure
- Reduction of ultrasonic signals has to be considered while determining the exact size of the discontinuities. Studies from the literature also point out the same conclusion.
- With these experiments, it can be concluded that, a discontinuity having at least 1,5 mm diameter can always be detected by ultrasonic testing made on a specimen having up to 26.5 μm Ra rough surface
- The exact locations of the discontinuities can always be measured by ultrasonic testing through surfaces having 0.5 to 26.5 μm Ra surface roughness.
- Using low frequency probes on rough surfaces give better results when compared with high frequency probes.
- Using two test frequencies for an ultrasonic test on rough surfaces will reduce the error made for correctly sizing the discontinuities.
- Incase the echo height is important measure for the test (amplitude of the sound pressure from backwall) then it is better to use grease instead of machine oil as a couplant even at rough surfaces. But low frequency probe usage should always be preferred with grease couplant on rough surfaces to avoid incorrect interpretation of the discontinuities.

- There is no directly proportional relation between ultrasonic signal amplitude reduction and increasing surface roughness. Ultrasonic signal reduction follows an exponentially decreasing path with increasing surface roughness because of insufficient coupling condition.

The other useful idea can be obtained from these tests is taking the situation visa versa, which means, to aim measuring surface roughness instead of detecting discontinuity. It is known that conventional surface roughness measuring devices uses optical characteristic of surfaces which gives usually rms roughness, and mechanical movement of stylus which gives Ra roughness. Considering the test results, reduction in ultrasonic signal amplitude with increasing roughness may be used to measure surface roughness. If a relation between these values can be obtained than measuring roughness maybe achieved. Incase there is no relation; standard tables can be formed by collecting empirical data. But a further study is necessary to find availability of this subject.

A further study with different testing methods can be helpful to fully reveal the effect of surface roughness and the ways to decrease or eliminate its effect. One study can examine the difference in results obtained from differently machined surfaces together (e.g. surfaces machined by grinding, electro erosion, shaper, blaster, periodic or non periodic roughness style etc.) Another study can examine the case by using various couplant types. Another study can consider using probes having different crystal diameter and different frequencies together. As it can be understood from above items, the results concluded from this study can only be useful to understand the effect of periodic surface roughness made by milling on ultrasonic testing. There are many open points as listed above for testing rough surfaces ultrasonically, and these points should be examined together in order to fully understand ultrasonic testing of rough surfaces phenomena.

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Last Login Date: 26.12.2005

APPENDIX A

Table A.1 Acoustical Properties of Some Metals [1]

Metals	Longitudinal Velocity		Shear Velocity		Surface Velocity		Density g/cm^3	Acoustic Impedance g/cm^2-sec x10^5
	cm/μs	in/μs	cm/μs	in/μs	cm/μs	in/μs		
Aluminum	.632	.2488	.313	.1232	***N/A***	***N/A***	2.70	17.10
Brass	.428	.1685	.230	.0906	***N/A***	***N/A***	8.56	36.70
Brass, Half Hard	.383	.1508	.205	.0807	***N/A***	***N/A***	8.10	31.02
Brass, Naval	.443	.1744	.212	.0835	***.195***	***.0770***	8.42	37.3
Bronze, Phospho	.353	.139	.223	.0878	***.201***	***.0790***	8.86	31.28
Copper	.466	.1835	.0890	.035	***.193***	***.0760***	8.93	41.61
Gold	.324	.1276	.120	.0472	***N/A***	***N/A***	19.32	62.6
Iron	.590	.2323	.323	.1272	***.279***	***.110***	7.70	45.43
Iron, Cast	.480	.189	.240	.0945	***N/A***	***N/A***	7.80	37.44
Lead	.216	.085	.070	.0276	***.0630***	***.0248***	11.4	24.62
Magnesium	.631	.2484	N/A	N/A	***N/A***	***N/A***	1.74	10.98
Nickel	.563	.2217	.296	.1165	***.264***	***.104***	8.88	49.99
Platinum	.396	.1559	0 .167	N/A	***N/A***	***N/A***	21.4	84.74
Silver	.360	.1417	.159	.0626	***N/A***	***N/A***	1.5	37.8

continued…

Table A.1 continued…

Silver, Nickel	.462	.1819	.232	.0913	***.169***	***.0665***	8.75	40.43
Silver, German	.476	.1874	N/A	N/A	***N/A***	***N/A***	8.70	41.41
Steel, 302 Cres	.566	.2228	.312	.1228	***.312***	***.123***	8.03	45.45
Steel, 347 Cres	.574	.226	.309	.1217	***N/A***	***N/A***	7.91	45.4
Steel, 410 Cres	.739	.2909	.299	.1177	***.216***	***.0850***	7.67	56.68
Steel, 1020	.589	.2319	.324	.1276	***N/A***	***N/A***	7.71	45.41
Steel, 1095	.590	.2323	.319	.1256	***N/A***	***N/A***	7.80	46.02
Steel, 4150, Rc14	.586	.2307	.279	.1098	***N/A***	***N/A***	7.84	45.94
Steel, 4150, Rc18	.589	.2319	.318	.1252	***N/A***	***N/A***	7.82	46.06
Steel, 4150, Rc43	.587	.2311	.320	.126	***N/A***	***N/A***	7.81	45.84
Steel, 4150, Rc64	.582	.2291	.277	.1091	***N/A***	***N/A***	7.80	45.4
Steel, 4340	.585	.2303	.128	.0504	***N/A***	***N/A***	7.80	45.63
Titanium	.607	.239	.331	.1303	***N/A***	***N/A***	4.50	27.32
Zinc	.417	.1642	.0949	.0374	***N/A***	***N/A***	7.10	29.61

APPENDIX B

Fig. B.1 Engineering Drawing of the Test Specimens