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Non-destructive Testing and Evaluation of Cast Materials

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ABSTRACT

In the industrial age of today, non-destructive evaluation of materials, components, and assemblies has become increasingly important, and plays a crucial role, be it in space, power, oil, automobile, or steel sector. As the consequences of component failure are more serious than ever, the integrity of component has to be evaluated and assessed at every stage of its production. Presence of harmful defects, tensile residual stress, and unwanted microstructure affects the integrity of any component. Hence, assessment of defects, and evaluation of residual stress and microstructure are very essential. Many nondestructive testing and evaluation techniques are being used for detection and characterization of defects, evaluation of residual stress, and assessment of microstructure. They provide a tool by which integrity evaluation, and assurance activities for components can be carried out. In this paper, an attempt has been made to present the basic concepts of non-destructive evaluation. The principles of different non-destructive test techniques have been discussed, and the application of these techniques for evaluation of castings has been highlighted.

INTRODUCTION

Testing and evaluation of cast products in a foundry industry has one primary objective. It is to make sure that parts being produced actually meet all required specifications established by the customer. Use of non-destructive testing and evaluation (NDT&E) as a means of quality control permits the industries to produce better quality products. Obviously, NDT&E in itself cannot produce a better product. However, if inspection works in close co-operation with the industry's quality control department and advises the department on any and all deviations in procedure, the quality control department can then make the necessary adjustments in process practice to ensure high quality products. Moreover

in order to prevent the excessive scrap products, it is necessary for the inspection department to catch the faulty product as soon as possible. In this way, the faulty product can be isolated so no further labour or time will be wasted on it, and secondly, the quality control department can make necessary corrections before too many products are poured.

The objective of inspection of in-service cast products/components is to make sure that the component or part in service will further satisfactiorly perform its intendted purpose. Several non-destructive test (NDT) methods are being used to ensure the integrity of in-service components. The interpretation of the data obtained byNDT during such inspection is performed to a large extent by using fracture mechanics concept. According to fracture mechanics, crack-like flaws present in the material grow under the conjoint action of stress and environment during service, and ultimately lead to failure of the component by growing to a critical size. The fracture mechanics concepts allow one to calculate the critical size of defect and enable to estimate the remaining life of the component.

Non-destructive testing (NDT) is generally used for finding , locating and sizing a flaw, whereas non-destructive evaluation (NDE) aims to identify and characterize the flaws and, consideration of physical mechanism and structure, to project future performance and reliability. The selection of a suitable NDT method or a combination of NDT methods first necessitates a clear understanding of the problem to be solved. There are six factors involved in selecting a NDT method[1]. They are: (1) the reason for performing the NDT, (2) the types of flaws of interest in the object, (3) the size and orientation of flaw that is rejectable, (4) the anticipated location of the flaws of interest in the object, (5) the size and shape of the object, and (6) the characteristic of the material to be inspected. Accordingly a suitable NDT method may be selected. In this paper several non-destructive techniques used for the inspection of castings are discussed. As it is important for the NDT inspector to be able to locate the source of the problem, the nature and type of discontinuities which can be expected in the material at each stage of casting are also briefly discussed. Further a brief outline of fracture mechanics methodology for integrity assessment is presented.

Defects in castings

The flaws which may be formed during casting can be classified as follows:

Non-metallic inclusions : The non-metallic inclusions within the molten steel which are caused by the impurities in the starting material, are lighter than the molten metal and rise towards the surface. Most of the non-metallics manage to rise to the top of the ingot but some are trapped within because they do not have the time to reach the surface before the molten metal above them is solidified. These inclusions are irregular in shape.

Porosity : It is spherical or nearly spherical shaped and is caused by the entrapped gas in the molten material. The appearance of porosity and non-metallic inclusions in an ingot are shown in Fig.1.

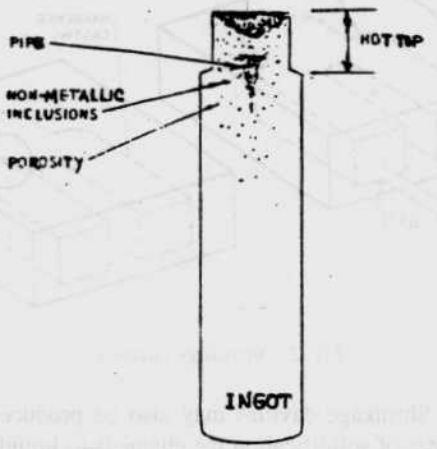

Fig. 1 : Porosity and non-metallic inclusions

Shrinkage cavities : Shrinkage cavities are formed during liquid to solid contraction. These flaws are not normally associated with gas formation but a high gas content will increase their extent. The shrinkage cavities may occur in these following forms.

Macro-shrinkage (piping): Liquid solidification and contraction in the mould will cause the formation of shrinkage cavities (piping). The molten material, after it is poured into the mould starts to cool and solidify. The solidification process starts from the surface and travels towards the centre of the ingot. On solidification the molten metal contracts. Since the centre of the ingot is the last to cool and solidify most of the shrinkage is concentrated in the centre. This results in the cavity called the 'pipe'. By properly designing the mould and by adequate hot topping, piping can be restricted to the top or to the feeder head. Piping may extend from the top towards the interior of the ingot along the axis. This is shown in Fig.1.

Centre-line shrinkage (filamentary shrinkage) : Wherever solidification cannot be correctly controlled and is not directional a coarse form of shrinkage may occur. These flaws may be extensive, branching, dendritic and interconnected. Filamentary shrinkage should theoretically occur on the centreline of the cast section but due to temperature gradients during solidification, the flaw may extend to the cast surface. Especially in alloys with a broad freezing range (such as bronze) shrinkage is more dispersed than centreline.

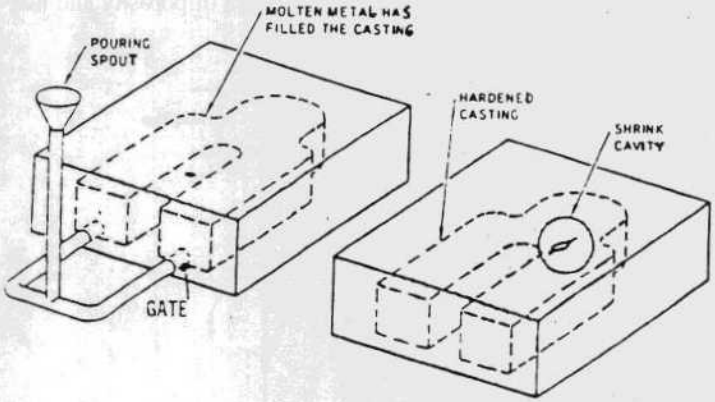

Fig. 2 : Shrinkage cavities

Microshrinkages : Shrinkage cavities may also be produced on a microscale. During the later stages of solidification the channels to liquid metal between the growing dendrite arms become progressively narrower. In some places the dendrite arms may bridge over and restrict the supply of liquid steel to the now isolated pools of liquid. The cavities that result are in very fine form and are called "microshrinkage". These occur between the dendrite arms (interdentritic) or at grain boundaries (intercrystalline) (Fig. 2).

Cold shut : Cold Shut is formed when molten metal is poured over solidified metal (see Fig.3). When the metal is poured, it hits the mould too hard and spatters small drops of metal. When these drops of metal hit higher up on the mould they stick and solidify. When the rising molten metal reaches and covers the solidified drops of metal a crack like discontinuity is formed. Cold shuts can also be formed by the lack of fusion between two intercepting surfaces of molten material of different temperatures.

Hot tear (Shrink crack) : Hot tear is caused by unequal shrinking of light and heavy sections of a casting as the metal cools. In a casting having light and heavy sections, the light sections being smaller solidify faster, they shrink faster pulling the heavier sections, which are hotter and not shrinking as fast, towards them (Fig.4). These cracks are discontinuous and generally in ragged form.

Cold or stress cracks : These cracks are formed when the metal is completely solid and are well defined and approximately straight. They are the result of large contraction stresses and are more likely to occur in large complicated shapes of castings. The cast analysis may be another factor for the stress cracks. Extreme care must be taken when alloying elements such as nickel, chromium,

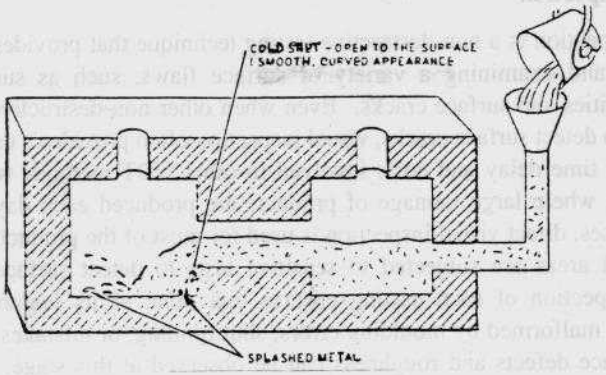

Fig. 3: Cold shut

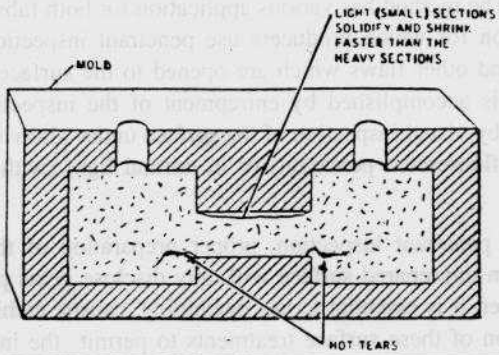

Fig. 4 : Shrink crack

vanadium and molybdenum are added to increase the hardenability of the alloy. These alloys affect the martensitic transformation temperature and may give rise to high stresses during the cooling cycle.

Blow holes : Blow holes are small holes on the surface of the casting and are caused by external gas emanating from the mould itself.

TEST METHODS

A number of NDT techniques are available for testing cast materials. Some of the widely used techniques include the followings.

Visual Inspection

Visual inspection is a non-destructive testing technique that provides a means of detecting and examining a variety of surface flaws, such as surface finish, discontinuities and surface cracks. Even when other non-destructive techniques are used to detect surface cracks, visual inspection often provides a useful supplement. The time delay and costs involved in other NDT methods would be unacceptable where large tonnage of products are produced each day. Typically in such cases, direct visual inspection is used for most of the production lots, and only small areas are subjected to sensitive tests to detect surface blemishes. Visual inspection of each casting ensures that none of its features has been omitted or malformed by moulding errors, shut running, or mistakes in cleaning. Most surface defects and roughness can be observed at this stage.

Liquid Penetrant Testing (LPT)

LPT is a non-destructive test method of revealing discontinuities that are opened to the surface. The method has various application for both fabricators and users. The basic reason for which producers use penetrant inspection is for locating cracks, pores and other flaws which are opened to the surface being inspected. This objective is accomplished by entrapment of the inspection liquid by the flaws followed by visual inspection of the surface under ultraviolet or black light (when using a fluorescent penetrant) or in normal light (with visible dye penetrant)[2,3].

For the use of penetrant inspection, proper preparation of the test surface is critical. LPT on unprepared surface will only disclose gross porosity and large cracks. However, it is essential to use machining, caustic etching, acid pickling or a combination of these surface treatments to permit the inspector to distinguish fine porosity and fine cracks. For example, in case of aluminium ingots and heavy plate sections use of acid pickle is recommended in preference to caustic etch.

Magnetic Particle Inspection (MPI)

Magnetic particle inspection is a method of locating surface and subsurface discontinuities in ferromagnetic materials. It depends on the fact that when the material or the part under test is magnetised, magnetic discontinuities that lie in a direction generally transverse to the direction of the magnetic field will cause a leakage field to be formed at and above the surface of the part. The presence of this leakage field, and therefore the presence of the discontinuity, is detected by the use of finely divided ferromagnetic particles applied over the surface, with some of the particles being gathered and held by the leakage field. This magnetically held collection of particles forms an outline of the discontinuity and generally indicates its location, size, shape, and extent. Magnetic particles are ap-

plied over a surface as dry particles, or as wet particles in a liquid carrier such as water or oil.

Magnetic particle inspection is a highly effective and sensitive technique for revealing cracks or similar defects at or just beneath the surface of castings made of ferromagnetic metals. The capability of detecting discontinuities just beneath the surface is important because such cleaning methods as shot or abrasive blasting tend to close a surface break that might go undetected in visual or liquid penetrant testing. Small castings can be inspected directly on bench type equipment that incorporates both coils and solid contacts. Critical regions of larger castings can be inspected by the use of yoke. coils or contact probes.

Ultrasonic Inspection

In this method a beam of high frequency sound waves are introduced into material for the detection of surface and interior flaws in the material. The sound wave travel through the material with some loss of energy (attenuation) and are reflected at interfaces. The reflected beam is displayed and then analysed to define the presence and location of flaws or discontinuities [4,5]. Fig. 5. illustrates typical ultrasonic indications from four types of flaws found in castings.

Ultrasound Attenuation

Coarse grained structures in thick plates, ingots and cast materials cause considerable increase in attenuation, mainly because of scattering and diffraction at

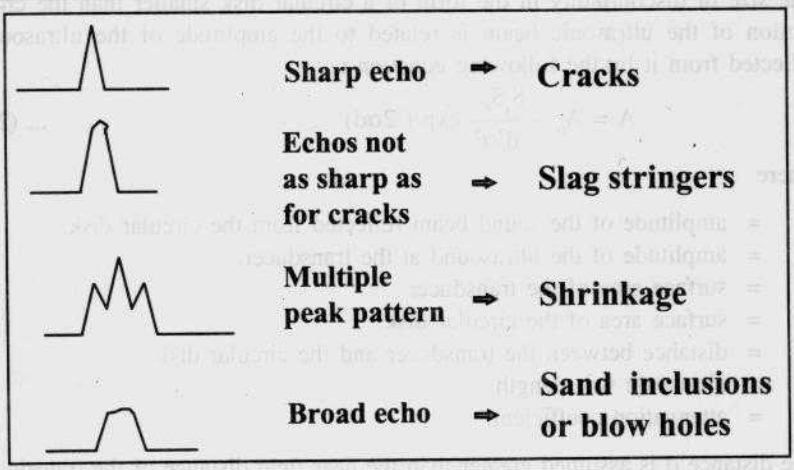

Fig. 5: Typical ultrasonic indications from four types flaws found in castings

grain boundaries. As a rule ultrasonic beam intensity decreases exponentially with metal travel distance. The manner in which ultrasound attenuates in metals influences discontinuity detection and material characterisation technique. Therefore it is often become necessary to establish laboratory or on-line attenuation measurement practices.

The ultrasonic attenuation coefficient for any solid material is determined by measuring the ultrasonic transmission through prepared specimen for different thickness using direct amplitude measurement. The attenuation coefficient is calculated from the following equation in decibel per millimetre as:

$$\alpha = \frac{20 \log (A_0/A)}{X} \qquad \ldots (1)$$

where, A_0 and A are ultrasound amplitudes before and after travelling through the material, X = travel distance. The measurement of attenuation coefficient are often used to obtain qualitative and quantitative information on the internal structure of the products.

Measurement of Discontinuity Size

In ultrasonic test, flat bottom holes are used to simulate natural discontinuities. The test instrument is calibrated using a series of reference standards in the form of cylindrical blocks containing flat bottom holes of specified sizes at different depths.Discontinuity size is determined by comparing the reflected signal amplitude with that reflected by a flat bottom hole at a similar depth.

The size of discontinuity in the form of a circular disk smaller than the cross section of the ultrasonic beam is related to the amplitude of the ultrasound reflected from it by the following equation :

$$A = A_0 \frac{S_s S_f}{d^2 \alpha^2} \exp(-2\alpha d) \qquad \ldots (2)$$

where

A = amplitude of the sound beam reflected from the circular disk.
A_0 = amplitude of the ultrasound at the transducer.
S_s = surface area of the transducer
S_f = surface area of the circular disk
d = distance between the transducer and the circular disk
λ = ultrasonic wavelength
α = attenuation coefficient.

The distance d is assumed greater than the near field distance of the transducer and 100 percent reflection occurs at the circular disk. In practice, however, reflector size can be obtained by use of a distance amplitude curve, produced by

measuring the ultrasonic amplitude reflected from flat bottom holes at different depths in a series of calibration blocks.

Monitoring Porosity

Individual pores do not produce distinguishable ultrasonic indications under products test conditions. The ultrasonic indication of centreline porosity is typically in the form of noise or so-called grass in the centre of A-scan display. This makes it difficult to distinguish between porosity and large grained structure that produces similar ultrasonic indications. It is common practice to verify the presence of porosity by monitoring the noise level and the reduction in amplitude of the back echo signal. For example, if the noise level reaches 50 per cent of the alarm level and the back echo is attenuated to 50% of its original amplitude, there is good chance that porosity is present in that sections of the material. However, plates with large grain structure might produce a similar effect and this could result in rejection of good material. In such cases ultrasonic data acquisition systems, which offer digital filtering, can be used to eliminates the frequency components of the incident ultrasound that might be particularly sensitive to the grain structure of the plate.

Signal processing technique may be used to more accurately verify the presence of porosity and also to approximate the size and volume fraction. This is done by measuring the changes in frequency dependence of the attenuation coefficient. Using a broad band transducer, the front and the back surface signals of the material are acquired and digitised. The frequency spectra of both signals are obtained by performing a Fourier transform. The frequency dependence curve of the attenuation coefficient is then obtained by deconvolving the back surface echo spectrum by that from the front surface. An attenuation coefficient value higher than normal verifies the presence of porosity. Quantitative measurements can be made by taking the slope of the attenuation curve or by comparing attenuation coefficient values with that from a reference standard. Another valuable quantitative method uses a inflection point that may appear on the attenuation versus frequency plot. For example, in cast aluminium, the average pore size is theoretically related to the frequency at inflection point by the following equation :

$$R = \frac{1.08}{f_p} \qquad \ldots (3)$$

where

f_p = the frequency of the inflection point (MHz)

R = the average pore radius (mm).

The factor 1.08 accounts for the Poisson's ratio of aluminium and scattering cross section of the porosity. The average volume fraction of porosity C, may be

determined by measuring the attenuation co-efficient at the inflection point and using the following equation.

$$C = 122\ \alpha_p R \qquad \ldots (4)$$

where

α_p = attenuation coefficient (nepers per mm)
R = average pore radius (mm)

The factor of 122 is related to the average cross section of the porosity and to the Poisson's ratio of aluminium.

Microstructure Characterization and Estimation of Mechanical Properties

Microstructure characterization is another interssting area of NDE. It can be done in situ without damaging the object by using replication microscopy or by using conventional optical microscopy technique with portable equipment. Other methods include ultrasonic wave velocity measurement. The velocity of ultrasonic transmission of a casting can be related to modulus of elasticity. In cast iron, the change from flake graphite to nodular graphite is related to an increase in both modulus of elasticity and strength, therefore, ultrasonic velocity measurement can be employed as a guide to nodularity.

Radiographic Inspection

It is based on the differential absorption of the penetrating radiation (x-ray or γ-ray) and is used to detect the features of a component or assembly that exhibits difference in thickness or physical density as compared to the surrounding material[7,8]. It is one of the most effective NDT method for quality control of castings.

Radiation Sources used in Casting Radiography

Gamma ray sources, especially Co-60 and Ir-192, are often used in casting radiography. These sources have some advantage (like simple apparatus, compactness, and independent from external power), over x-rays. However the use of x-rays are essential for some application. For example low energy (kilovolt) x-rays are used for testing light metals such as aluminium, and thin metal thickness of steel. High energy (megavolt) x-rays are used for steel having section thickness in excess of 20 cm. (please see table 1). However, the best way is to select the sources that produces desired result.

Defect Detection and Standards :

Radiographic inspection is a very effective means of detecting such defects as cold shuts, internal shrinkage, porosity, core shifts and inclusion in castings. For

example inclusions will appear on the radiograph as darker indication (inclusion less denser than the matrix) or lighter indication (inclusions more denser than the matrix). Sand inclusion and dross, which are non-metallic oxides appear on the radiograph as irregular dark, blotches, Shrinkage and cold shuts will appear on the radiograph as dark spot and crack respectively.

Table 1 : ASTM reference radiographs for different cast materials

Sl. No.	*Material*	*Section thickness [inch]*	*ASTM reference standard*	*Radiation source used*
1.	Aluminium and magnesium castings	1/4 to 2	E 1555	X-rays
2.	Aluminium and magnesium die casting	1/8 to 1	E 505	X-rays
3.	High strength copper base and nickel-copper alloy castings	upto 6	E 272	X-rays and Ir-192
4.	Tin bronze castings	Upto 2	E 310	X-rays and Ir-192
5.	Steel thin precision castings	1/8 to 3/4	E 192	X-rays
6.	Steel castings heavy walled	2 to 4 1/2	E 186	X-rays, Ir-192 and Co-60
7.	Steel castings heavy walled	4 1/2 to 12	E 280	X-rays, and Co-60
8.	Gray Iron castings	Upto 4	E 802	X-rays, Ir-192 & Co-60

The sensitivity, or the ability to detect flaws , of radiographic inspection depends on close control of the inspection technique including the geometric relationship among the points of x-ray emission, the casting and the x-ray imaging plane. The smallest detectable variation in metal thickness lies between 0.5 and 2.0% of total section thickness. Narrow flaws, such as cracks must lie in a plane

approximately parallel to the emergent x-ray beam. Aluminium alloy castings are ideally suited to examination by radiography because of their relatively low density. A given thickness of aluminium alloy can be penetrated with about one-third the power required for penetrating the same thickness of steel. Aluminium alloys are most often radiographed with an x-ray machine. Although gamma ray method is used to lesser extent than the x-ray method it is equally as effective for detecting flaws. Aluminium alloys are most often radiographed to detect same type of flaws that may exist in other type of castings i.e. conditions such as porosity or shrinkage which register as low density spots and appear blacker on the film than areas of sound spots. There exists standard reference radiographs to illustrate the types and degree of discontinuities that may be found in castings. These standard reference radiographs are available in ASTM standards and are listed in Table 1.

Eddy Current Testing

In this method the change of impedance of a test coil brought close to a conductive material indicates the eddy current induced by the coil and thereby indicates certain properties or defects of the material[9,10]. Eddy current test can supplement or sometime replace LPT for detection of surface connected discontinuities, but is not as sensitive to small open defects as LPT or MPI is. Because of the skin effect eddy current inspection is generally restricted to depth less than 6mm. The method is effective with both ferromagnetic and non-ferromagnetic materials. It can also be used for the sorting of mixed alloys and for the evaluation of overageing or heat damage to metals and alloys.

Eddy current Conductivity and hardness testing methods are commonly used to asses heat damage of various heat treatable alloys. In order to permit a quantitative assessment of heat damaged material, the establishment of conductivity, hardness and strength (CHS) relationship is essential for each alloy. This is necessary because of the interplay of several factors that can affect the CHS relationship in a variety of ways. Eddy current or coercive force can be used to detect many changes in casting structure and properties. Eddy current indications are useful for evaluating pearlite and carbide in iron matrix.

Acoustic Emission Testing

Acoustic emission testing is based on the fact that solid materials emit sound or acoustic emission when they are mechanically or thermally stressed to the point where deformation or fracturing occurs [11, 12]. These elastic waves can be picked up and analysed by an aoustic emission test system to monitor the condition of the material under stress. The technique being capable of detecting and locating dynamic defects, has great potential for on-line integrity monitoring of industrial components. For example pressure vessel and pipes are routinely monitored with

the help of AE with regard to their fitness and integrity[13-15]. There have been also a few studies of AE during solidification of aluminium alloys. It was Suggested that AE was generated by formation of porosity. It was found that AE was proportional to the volume fraction of porosity. The lower hydrogen solubility of solid aluminium results in a hydrogen supersaturation in the melt close to the liquid-solid interface. The relief of this supersaturation act as a driving force for hydrogen bubble formation in a role analogous to that strain energy reduction in the formation of cracks.

FRACTURE MECHANICS METHODOLOGY FOR EVALUATION OF NDT RESULTS

The cracks that are detected by NDT may grow with time due to operation mechanism such as fatigue, stress corrosion or creep, and with increase of crack length the residual strength of the component would decrease. The integrity of the component will be impaired, when the residual strength falls to design or operation stress level. The situation can be schematically depicted as shown in Fig. 6. With reference to this figure, it may be noted that the strength of the singularity in the stress field at the crack tip is characterized by stress intensity factor, K, which can be expressed as a function of the applied stress σ, and the crack length, a, through relation of the form[16].

$$K = \sigma \sqrt{\pi a}\, Y \qquad \ldots (5)$$

where Y is a geometric function dependent on the component configuration and

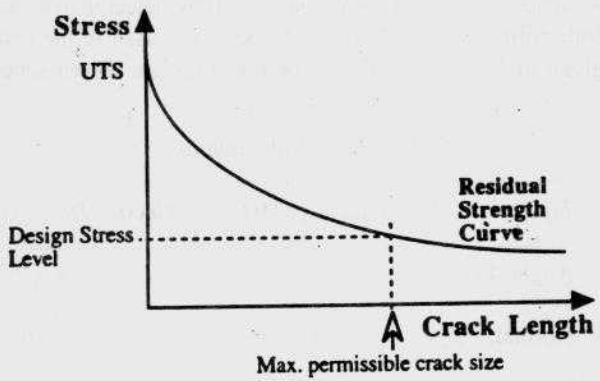

Fig. 6 : Decrease in residual strength of components on increase of crack length

the crack length. For all materials a citical value of the stress intensity factor K_c exists beyond which the stability of cracks contained in them cannot be ensured. Hence, K_c can be as the limit up to which an applied stress intensity factor may be tolerated without compromising the integrity of a component. Substituting, K_c for K for a range of crack length the maximum stress that can be endured by a component can be obtained. Similarly to obtain the maximum permissible crack size, K_c and the service stress can be substituted in to equation (5) To obtain information on the life time of a component, the time dependent of the crack growth process has to be characterized. For example, for crack growth through fatigue, the crack growth per stress cycle, da/dN, can be related to ΔK (obtained by using $\Delta\sigma$ instead of σ in equation (5)) through equation of the form.

$$\frac{da}{dN} = C.\Delta K^m \qquad \ldots (6)$$

where, c, and m, are constants. Such equation can be rearranged and integrated as follows, to estimate the remaining life N_R of the component.

$$N_R = \int_{a_0}^{a_c} \frac{da}{C.\ \Delta k^m} \qquad \ldots (7)$$

In the above equation a_0 is the initial crack length and a_c is the maximum permissible crack length.

CASE STUDY

Ultrasonic Testing of a Rail Manufactured from Concast Billet

In order to asses the integrity of a in-service rail, which was manufactured from concast billet, a piece of it about 2m length was ultrasonically tested at NML. The test was carried out using Echograph 1030 flaw detector from Karl Deutsch, Germany. Both normal and angle beam probes were used in the test. The probe details are given in Table 2 and the probe positions are shown schematically in Fig.7.

Table 2 : Probe details

Probe	*Type*	*Frequency (MHz)*	*Crystal Dimensions (mm)*
A	Angle 45°	2	8 x 9
B	Normal	4	ϕ 6
C	Normal	4	ϕ 24

The test was started with probe A. It was placed on the top surface of the rail as shown in Fig. 7, and was moved along the rail length starting from one end to the other end. A large number of flaws (1 to 39) were detected by this probe. They are listed in Table 3. A high gain approach was used to detect these flaws, and accordingly a gain of 80dB was used for this test. The test was then carried out using probe B. The test surface here was same as that for probe A. By this probe flaw No. 3, 37, 38, 41, and 42 only were detected (see Table 3). Finally the test was conducted using probe C. The scanning surrace here was the side of the rail head as showing Fig. 7. All the flaws except flaw No. 3, 37 and 38 (see Table 3) were detected by this probe. The gain was set at 90 dB for both probes B and C.

As can be seen in Table 3 that a total number of 41 flaws were detected over a length of 2 metre rail. Out of these 41, 36 have vertical orientation 2 have longitudinal orientation and 3 have tranverse orientation. This shows that most of flaws were vertical cracks located at a depth of 18-25 mm from the track surface at the centre line. These flaws are very fine cracks having a length of about 3-5 min and are jagged. This is the reason, why a high gain (above 80dB) was required to detect these flaws. A typical view of one of the crack having horizontal orientation is shown in Fig. 8. This was obtained by transversely slicing the rail, extracting the rail head and polishing it.

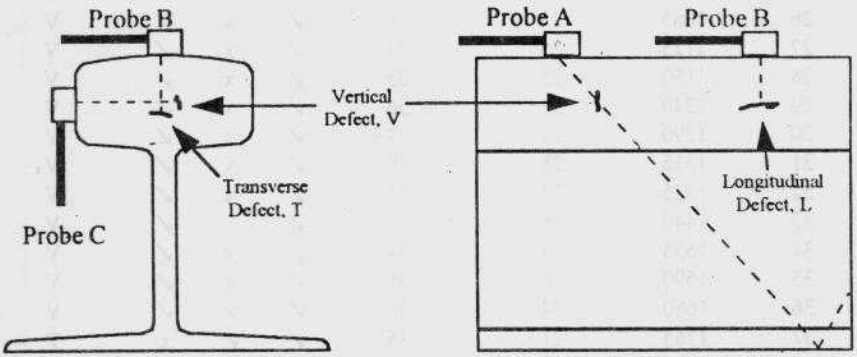

Fig. 7 : Schematic view of probe positions

Table 3 : Ultrasonic Test Results

Flaw Number	Distance from from weld end (mm)	Distance from top surface (mm)	Distance from side (right) (mm)	Detected by probe			Type of flaws
				A	B	C	
1	150	14	35	✓	x	✓	V
2	170	21	35	✓	x	✓	V
3	215	21	35	✓	✓	x	T
4	300	16	34	✓	x	✓	V
5	345	23	35	✓	x	✓	V
6	380	21	35	✓	x	✓	V
7	465	25	34	✓	x	✓	V
8	535	28	34	✓	x	✓	V
9	555	18	34	✓	x	✓	V
10	600	25	34	✓	x	✓	V
11	610	25	35	✓	x	✓	V
12	625	18	35	✓	x	✓	V
13	740	18	36	✓	x	✓	V
14	745	17	35	✓	x	✓	V
15	755	14	36	✓	x	✓	V
16	785	28	35	✓	x	✓	V
17	805	25	35	✓	x	✓	V
18	840	21	36	✓	x	✓	V
19	865	25	34	✓	x	✓	V
20	880	28	35	✓	x	✓	V
21	910	25	35	✓	x	✓	V
22	940	25	35	✓	x	✓	V
23	955	21	36	✓	x	✓	V
24	1000	19	34	✓	x	✓	V
25	1060	21	35	✓	x	✓	V
26	1085	21	36	✓	x	✓	V
27	1125	25	34	✓	x	✓	V
28	1150	25	35	✓	x	✓	V
29	1240	21	36	✓	x	✓	V
30	1290	25	34	✓	x	✓	V
31	1315	28	36	✓	x	✓	V
32	1325	23	35	✓	x	✓	V
33	1440	18	36	✓	x	✓	V
34	1555	19	34	✓	x	✓	V
35	1590	20	35	✓	x	✓	V
36	1680	24	35	✓	x	✓	V
37	1765	21	35	✓	✓	x	T
38	1800	20	35	✓	✓	x	T
39	1990	18	35	✓	x	✓	V
40	430	21	35	x	✓	✓	L
41	700	19	35	x	✓	✓	L

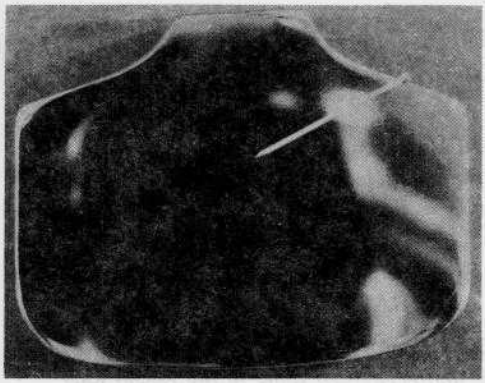

Fig. 8 : Macrophotograph of polished rail head showing a vertical crack

CONCLUDING REMARKS

In this paper various non-destructive techniques used for inspection of castings are discussed. Since it is not practically possible to extend the discussion to every details of all the techniques, the extents of the discussion are kept to the minimum.

REFERENCES

(1) Metals Handbook Vol.11, ASM (1976)
(2) Non-destructive Testing Handbook, Vol.2, "Liquid Penetrant Testing", ASNT (1982).
(3) Carl E. Betz, "Principles of Penetrants", Photopress Inc., Chicago, (1948).
(4) Krautkramer J., and Krautkramer H., Ultrasonic Testing of Materials" , Springer, Berlin (1977).
(5) D. Ensminger, "Ultrasonics" Marcel Dekker Inc., New York (1973)
(6) Nondestructive Testing Handbook, Vol.7, "Ultrasonic Testing" ASNT(1991).
(7) J.C. Dockley, "An Introduction to Industrial Radiography", Butterworth Co.Ltd., London (1964).
(8) Non-destructive Handbook Vol.3 "Radiography and Radiation Testing", ASNT(1985).
(9) M.L. Burrow , "A Theory of Eddy current Flaw Detection", University Microfilms Inc., (1964).
(10) Non-destructive Testing Handbook, Vol. 4, "Electromagnetic Testing ", ASNT (1986).
(11) Non-destructive Testing Handbook, Vol.5, "Acoustic Emission Testing", ASNT (1987).
(12) Waddley H. N. G. Scruby C. B., Speak J. H. "Acoustic Emission for Physical Examination of Metals" International Metals Review, No. 2, (1980), pp. 41-64.
(13) ASME Boiler and Pressure Vessel Code, Section V, "Nondestructive Examination" (1989).
(14) NML Internal Report No. NML/MTC/1.2/AE/97, "Acoustic Emission Monitoring During Hydrotesting of a LPG Horton Sphere", (1997).
(15) Parida N., "Structural Integrity Monitoring by Acoustic Emission", Nondestructive Evaluation of Materials, Eds. A. Mitra, N. Parida, D.K. Bhatacharya, and N.G. Goswami, NML, Jamshedpur, 1997, pp. 131-146.
(16) Tada, H., Paris P.C. and Irwin G.R. "The Stress Analysis of cracks Handbook", Del Research Corporation, Hellertown, Pa (1970).