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Non – Destructive Evaluation of Rolls of Hot Strip Mill of Tata Steel

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ABSTRACT

Performance of rolls in an Integrated Steel Plant like Tata Steel affects many plant performance measures i.e. mills down time (which affects plant productivity), rejection of rolled products, roll dressing time, consumption of rolls / ton of steel rolled etc. In order to ensure the supply of the rolls without harmful flaws, NDT techniques, particularly Ultrasonic and Eddy Current, were developed and implemented on the shop floor to improve the plant performance by reducing their failure in the mill. Indefinite Chilled Cast Iron Double Poured Work Rolls of finishing stands, High Chrome Iron as well as Chrome Steel Work Rolls of early finishing and roughing stand were evaluated for their shell / core disbond as well as surface cracks using these techniques. High Speed Steel rolls under trial in the finishing stand F2 were also evaluated for their surface cracks using an eddy current inspection method developed at R&D Division of Tata Steel..

1.0. INTRODUCTION

The integrity of rolls of HSM / CRM affects the mills performance in terms of mills productivity and availability, inventory costs, man and machine hour costs and also the quality of the rolled products. Immediately after commissioning of the Hot Strip Mill at TATA STEEL, due to frequent failure of rolls, the mill suffered a lot in terms of mills productivity and availability. A need was felt to check the integrity of these rolls by NDT techniques at the roll shop of HSM by standardization of the NDT techniques (ultrasonic and eddy current).

1.1. Factors Affecting Damages in the Rolls

1.1.1. Shell/Core disbond in double poured rolls :

These rolls are centrifugally cast in which two dissimilar metals Shell and Core are bonded with each other. The quality of this metallurgical bond depends on foundry variables like molten metal temperature, shell and core metal weights poured, spun cycle, quality of flux applied on the hot shell etc. In case of poor bond or disbond area on the shell/core interface, when the roll diameter approaches scrap diameter, under the influence of internal stresses, the disbond size may become critical, initiate crack propagation leading to roll failure due to spalling.

1.1.2. High Thermal Stresses :

During each rotation, work rolls of early finishing stands or roughing stands experience different temperatures at different locations on the roll surface which leads to thermal shocks and hence generation of fire cracks. Fire cracks are generally found on the rolls of roughing and early finishing stands where the temperature of the rolled slab is high. During roll rotation, maximum temperature of the roll surface which is in contact with the hot slab have been reported as 613 ^{0} C against the minimum roll surface temperature of 70 ^{0} C, after passing through the water cooling zone in the early finishing stands F1 – F3. It has been reported that the usual depth from the surface of rolls at which the temperature drops to 320 ^{0} C (where there is 15 % drop in hardness when compared with room temperature hardness) is 0.20 – 0.72. mm[1]. This results into thermal stresses leading to fire cracks in the rolls. If such cracks join the poor quality shell / core bond interface, a part of the shell material can come out from the roll. Under the influence of internal stresses, the size of these cracks may become critical leading to roll failure.

1.1.3. Abnormal Mills Behaviour

Besides the damage mechanisms as discussed above, abnormal mill behaviour during cobble or power trip etc. can also damage the rolls. Bruise/soft spots are induced on a roll body surface when the temperature of that surface area during mill service exceeds the tempering temperature used by the roll manufacturer to obtain the desired hardness level. A residual stress within the bruise is created as the retempered martensite contracts from the adjacent roll material. A stress crack (fine crack) is initiated which further propagates circumferentially generating a fatigue path leading to brittle fracture i.e. spalling.

During cobble, high loads (exceeding the normal loads), adhering metal weld on the surface etc. localized contact stresses are developed which lead to crack initiation and propagation leading to spalling.

2.0. NON – DESTRUCTIVE EVALUATION OF ROLLS

Hetchman Paul et. al.[2] has reported measurement of surface crack depths in rolls using ultrasonic surface wave probes having different frequencies. Takada Hazime et. al.[3] reported the use of on-line ultrasonic inspection system for the measurements of surface crack depths in high speed steel rolls in which broad band surface wave probe was used. On-line automatic inspection systems (EMAT ultrasonic and eddy current) for checking soundness of the back up rolls at roll shop has been reported by K. Berner et. al.[4]. Most of the advanced mills in Europe, USA and Japan use on-line NDT (ultrasonic and eddy current) systems and acceptance norms are based on the calibration blocks with artificial defects.

2.1. Ultrasonic Evaluation of Shell / Core Disbond in Work Rolls of HSM

2.1.1. Theoretical aspects :

When an ultrasonic wave passes through a medium, due to the resistance offered by the medium, the ultrasonic wave gets attenuated. Depending upon the characteristics of the medium, the extent of attenuation varies. The resistance is characterized by “acoustic impedance” and ultrasonic waves get reflected from the point where there is a change in the acoustic impedance. Since the shell/core interface provides substantial change in impedance, some parts of ultrasonic waves are reflected and displayed as a rectified signal on a calibrated CRO screen of the ultrasonic instrument, where x-axis is the time scale and y-axis is the amplitude of ultrasonic signal.

The acoustic impedance (Z) of a material is given by the product of material density (ρ) and velocity (v) of ultrasonic wave in that material.
$Z = \rho \cdot v$ ---------------------------------(1)

If subscripts 1 and 2 denote the parameters for material and ultrasonic waves for shell and core materials of centrifugally cast double poured rolls respectively,

For shell, $Z_1 = \rho_1 \cdot v_1$ ------------(2) and for Core, $Z_2 = \rho_2 \cdot v_2$ ------------------(3)

Reflection Co-efficient, R is given by , $R = (Z_2 - Z_1)^2 / (Z_2 + Z_1)^2$ --------------(4)

The value of R = 0.00137 in case of good bond and
= 0.99996 in case of disbond assuming air in between shell and core metal.

These theoretical values are difficult to achieve in conventional ultrasonic flaw detection. However these differences in 'R' can be indicated by the amplitude of the shell / core interfacial echo.

2.1.2 Standardization of ultrasonic instrument

Fig. 1 shows a schematic diagram of a calibration block made of Centrifugally Cast Double Poured Roll material with Indefinite Chilled Cast Iron as shell and S G Iron as core. The dimensions and locations of side drilled and flat bottom holes of 4 mm diameter have also been shown in Fig. 1. The dB setting for the equipment Krautkramer Model USD 10 of roll supplier and Krautkramer Model USM 3S of HSM Roll Shop has been shown in Table 1.

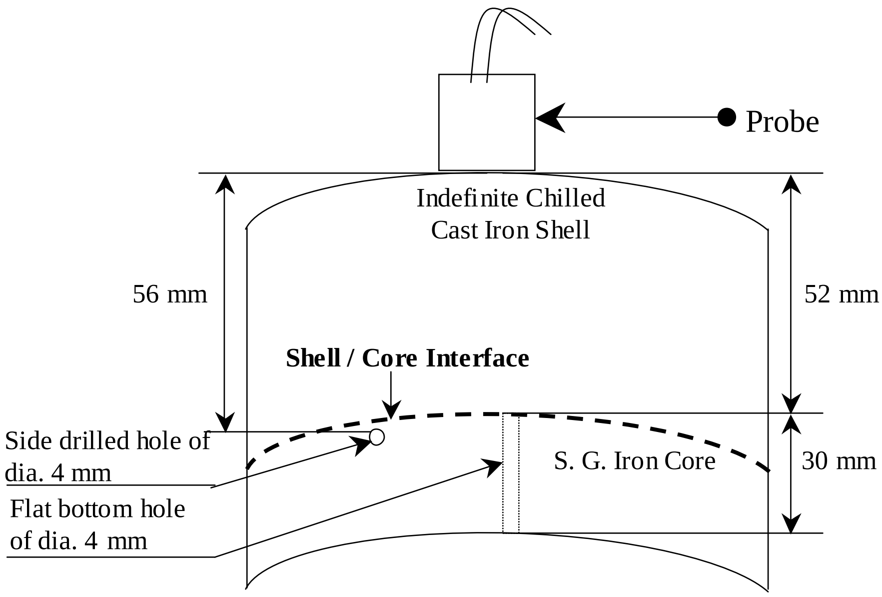

Fig. 1 : Schematic diagram of a calibration block made of Centrifugally Cast Double Poured Roll material.

Table 1. Gain setting to bring the echo from the reference reflector at 30 %

Reference reflector	Krautkramer Model USD 10 Normal Probe of 2 MHz, 25 mm diameter	Krautkramer Model USM 3S T / R Probe of 4 MHz, 25 mm diameter
Side drilled hole , dia. 4 mm	44. 1 dB	54. 1 dB
Flat bottom hole, dia. 4 mm	50. 0 dB	60. 0 dB

2.1.3. Measurements on Rolls :

The shell/core interfacial echo in ultrasonic testing is an indicator for measuring bond quality. A good bond roll will show a lower interfacial echo, whereas a poor bond roll will show a higher interfacial echo. In case of disbond area more than the probe crystal diameter, multiple reflection echoes may appear on the oscilloscope screen of ultrasonic flaw detector. Since it is difficult to cut a sample from a new roll, a reference roll was selected from a scrapped good roll which had given satisfactory life in service. Investigations were carried out for:

- Ultrasonic evaluation of all failed rolls, particularly due to poor shell / core bond leading to spalling.
- Ultrasonic evaluation of new in coming rolls and
- Ultrasonic evaluation of the rolls in service.

The test results are shown in Fig. 2.

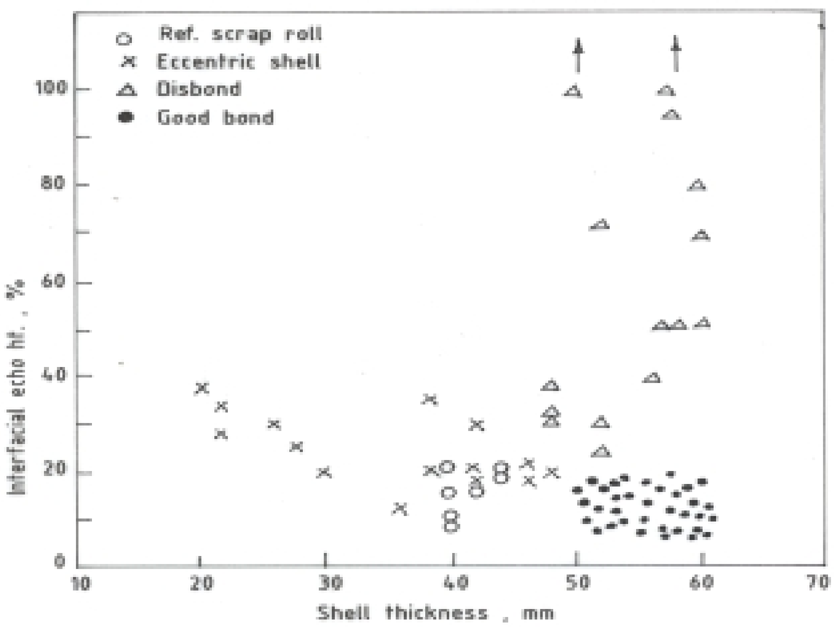

Fig. 2: Shell / core interfacial echo heights for different used and failed, as well as new Indefinite Chilled Cast Iron rolls of Hot Strip Mill.

2.2. Ultrasonic Evaluation of Surface Cracks in Rolls by Surface wave / Angle Probe

Usually depth of penetration of theses surface (Rayleigh) waves is one wavelength below the roll surface. The surface cracks with depth less than one wave length of ultrasound can be measured if the amplitude of the reflected signals from these cracks is properly calibrated.

2.2.1. Standardization of Ultrasonic Instrument :

To calibrate the ultrasonic equipment, calibration blocks with various step 0.55 to 3.54 mm were fabricated from mild steel. Fig. 3 shows the response of ultrasonic waves towards the various step of calibration blocks in terms of % HSH (Full Scale Height) on oscilloscope screen.

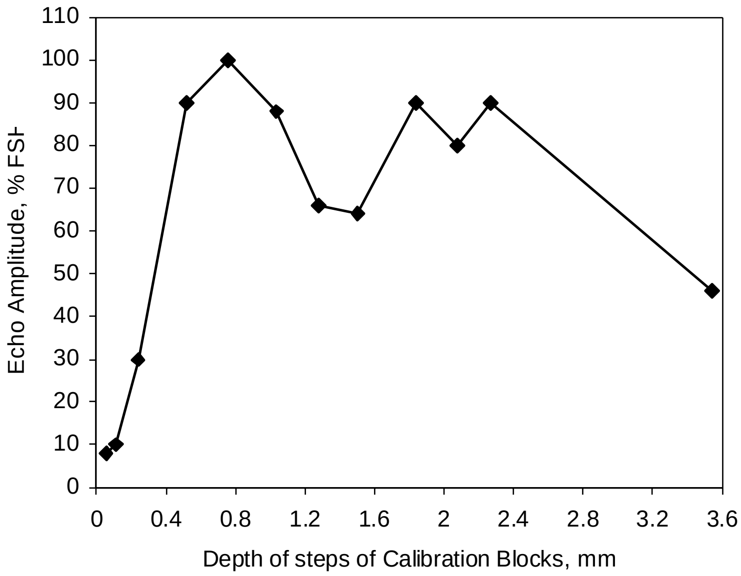

Fig. 3: Variation in Echo Amplitude (% FSH) in the calibration blocks with steps of varying depths, using 2 MHz, Surface Wave Probe at 49 dB Attenuator setting

The graph shows that there is gradual increase in echo amplitude with increase in the depth of the step up to ½ wavelength of the ultrasound (= 0.7 mm), beyond which there is decrease in the echo amplitude with increase in step depth. Further, beyond one wave length, there is no systematic response of ultrasonic waves, which can be used for crack depth measurement. However, the crack depths up to 0.7 mm can be measured using this calibration curve. By lowering the frequency of the surface wave probe, the depth of ultrasonic surface wave penetration can be increased and higher crack depths can be measured. For further deeper cracks, more than 1.4 mm, 80°, 70°, 60°, 45° probes can be tried.

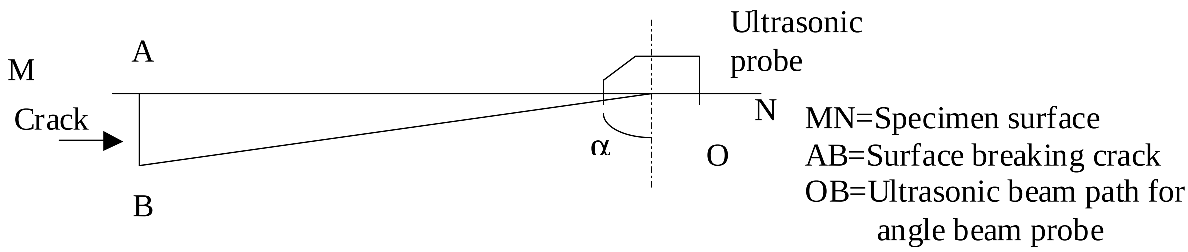

Fig. 4 : **Schematic diagram showing measurement of crack depth using angle beam probe.**

As shown in Fig. 4, Crack Depth, AB = OB cos α, where α = probe angle and OB = beam path. Considering minimum detectable beam path as 10 mm, for the commercial flaw detectors, minimum detectable crack depths using different beam angles are shown in Table2.

Table 2 : Maximum measurable crack depth using surface wave and minimum measurable crack depth using angle probes

Surface Wave probes		Angle Beam probe at 2 MHz frequency	
Probe Frequency	**Max. Crack depth measured**	**Probe Angle**	**Minimum detectable crack depth, mm**
4.0	0.35	80°	1.74
2.0	0.70	70°	3.42
1.0	1.4	60°	5.00
0.5	2.8	45°	7.07

2.2.2. Measurements on Rolls :

Fig. 5 (a) and (b) show a schematic diagram for measurement of the surface crack depth of a typically oriented crack using ultrasonic NDT method. The orientation of the crack path caused weak signal at probe position 2, whereas it was a strong at probe position 1. Crack depth could also be measured using this technique. Since the crack path was in a direction along the barrel length, its depth could also be found using normal probe as shown in Fig. 5 (b).

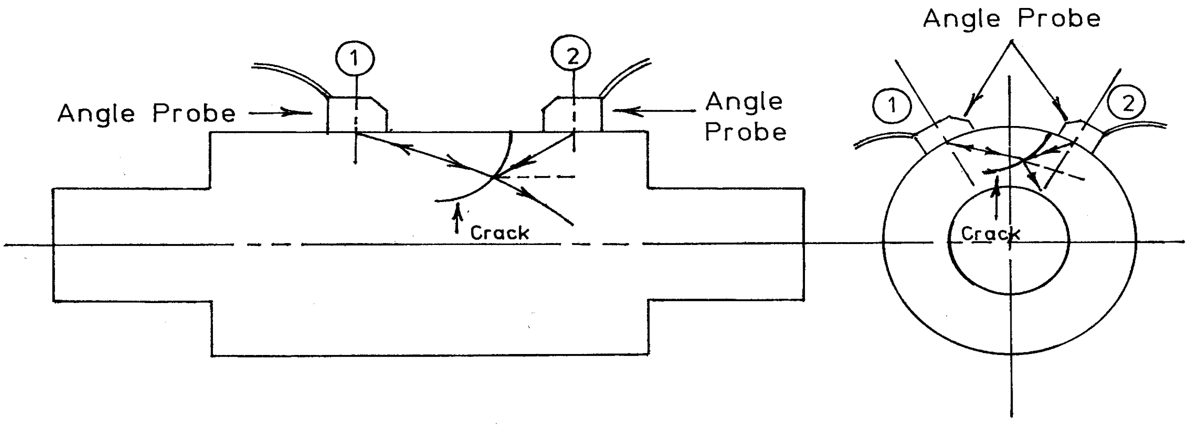

Fig. 5 (a) : **Ultrasonic measurement of an oruiented surface crack.**

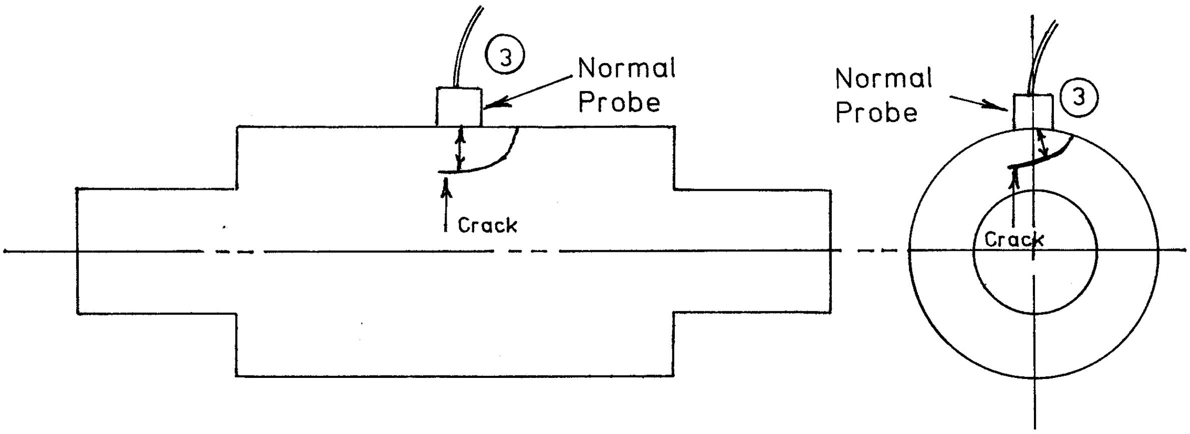

Fig. 5 (b) : Same as in Fig. 5 (a) using normal probe.

During one mill interruption, ultrasonic evaluation revealed that High Chrome Steel rolls of Roughing Stand developed crack depths in the range 13 – 35 mm, whereas Indefinite Chilled Cast Iron rolls of finishing stand F4 and F6 developed fire cracks in the range 2 – 14 mm.

2.3. Detection and Measurement of Surface Cracks in Rolls by Eddy Current

2.3.1. Theoretical aspects [5] :

Eddy currents are the induced electric currents which are generated in a conducting material due to change in the magnetic field. An AC source is applied to an inspection excitation coil so that the magnetic lines of force penetrate into the specimen conducting surface providing a good magnetic coupling as shown in Fig. 6.

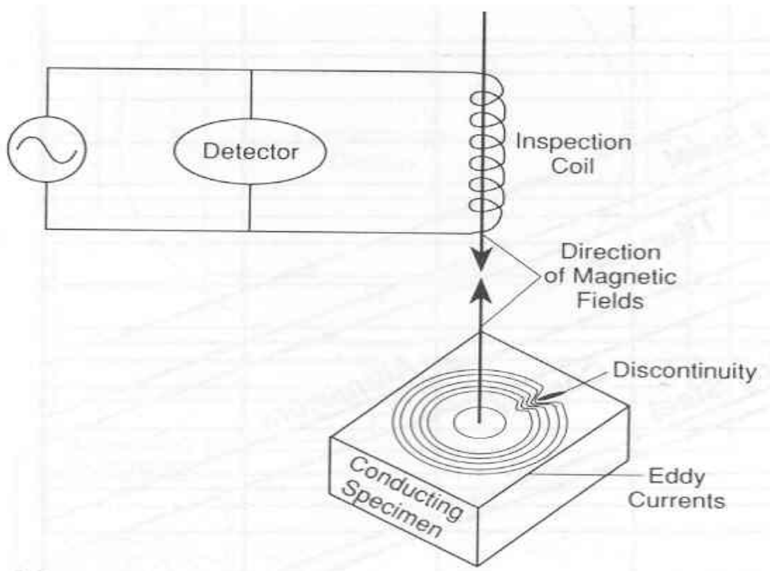

Fig. 6 : Schematic diagram of an eddy current testing of a specimen.

Eddy currents circulate in the specimen surface and are modified by the presence of discontinuities.(i.e. surface cracks). Eddy currents flow parallel to the plane of the windings of the coil. The detector instrument notes changes with time variation of voltage and current in the specimen coil.

The depth of penetration of eddy current (δ) in meters, within a material is given by

$$\delta = 50 \sqrt{\frac{\rho}{f\mu_r}} \quad \text{-------------------------------}(9)$$

Where, ρ = electrical resistivity in ohm-cm
f = frequency of AC in hertz and
μ_r = magnetic permeability of the material

The depth of penetration (δ) increases with increase in electrical resistivity (ρ), decrease in magnetic permeability (μ_r) and frequency (f) of A. C. current of material. In rolls, materials microstructure influences the magnetic permeability and resistivity and hence the depth of eddy current penetration.

2.3.2. Standardization of the Eddy Current Tester :

For detection and measurement of surface cracks in High Speed Steel rolls, a calibration block as shown in Fig. 7 made of special high speed steel with composition similar to that of High Speed Steel roll material was made. Fig. 8 shows the photo micrograph of such block.

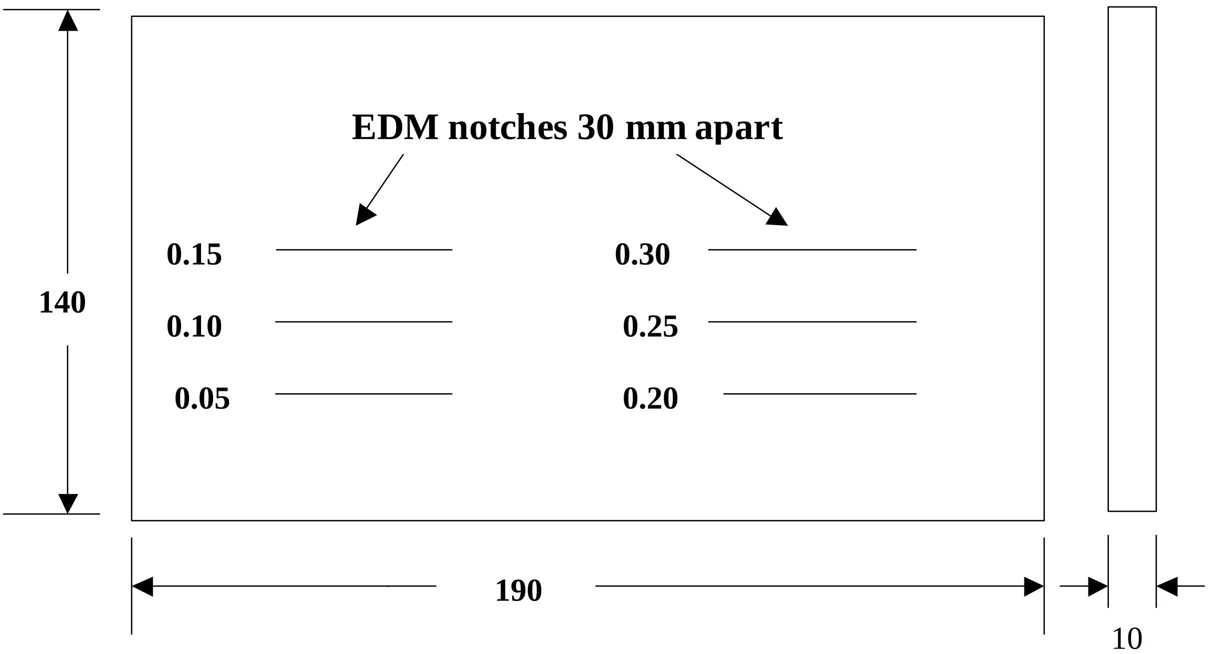

Fig. 7: Calibration block made of HSS roll material with EDM notches for repairing calibration curves to predict crack depth in HSS rolls of Hot Strip Mill

Fig. 8: **Microstructure of special high speed steel calibration block at magnification x 400 showing complex carbide of Fe, W, V and Cr in temper martensitic matrix (Etchant : 3% Nital).**

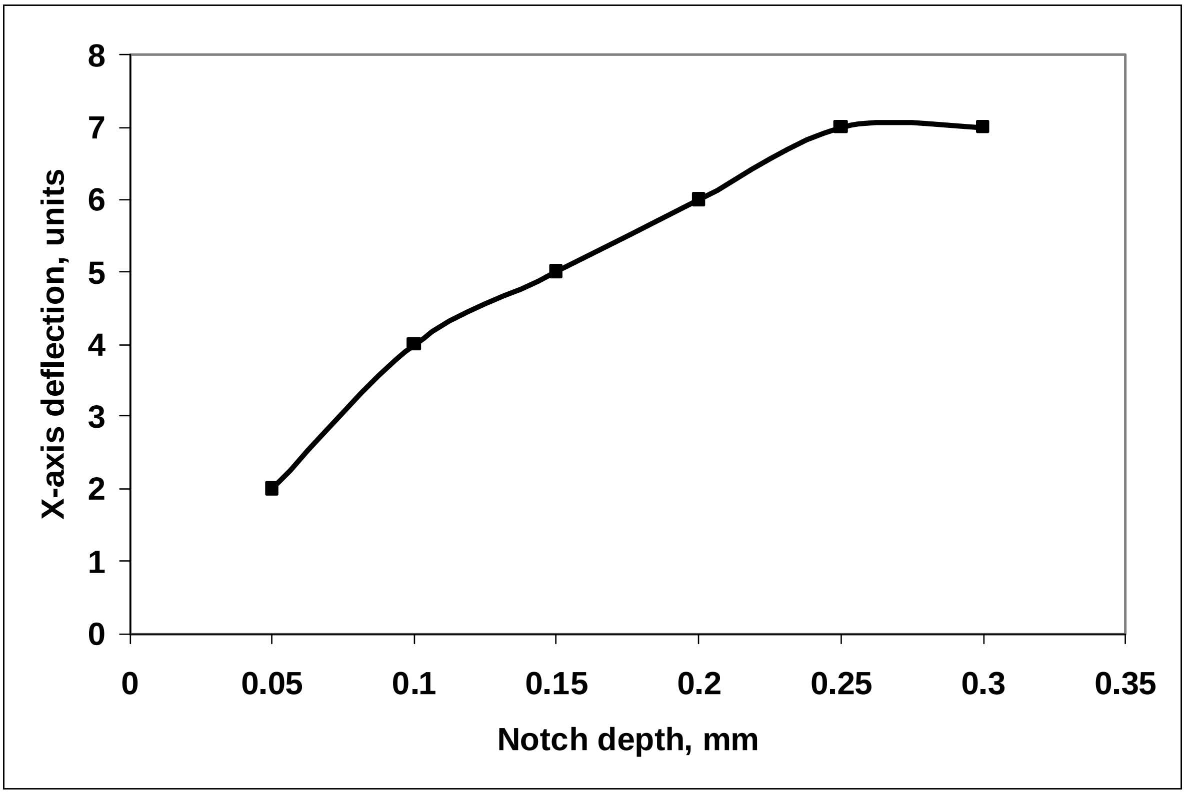

Fig. 9: **Effect of eddy current response at 64 KHz on EDM notches with depths 0.05 – 0.3 mm.**

As obvious form Fig. 9, there is gradual increase in the eddy current response in terms of X – axis deflection with increase in the notch depth up to 0.25 mm beyond which there is no change in the eddy current response. This indicates the limit of the eddy current penetration and the instrument can be calibrated for measuring crack depth up to 0.25 mm only using 64 kHz frequency. Similar trend is observed using 128 kHz as shown in Fig. 10, but the limit of eddy current penetration was observed to be 0.2 mm only.

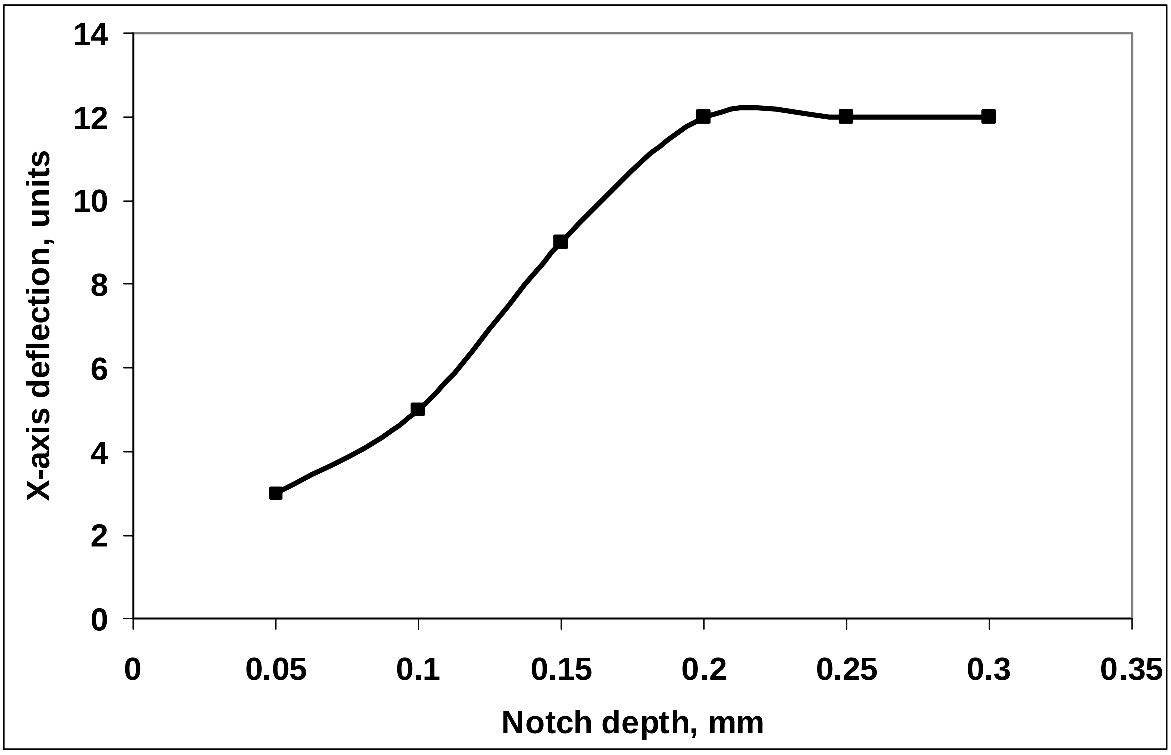

Fig. 10 : Effect of eddy current response at 128 kHz on EDM notches with depths 0.05 – 0.3 mm.

Fig. 11 (a) and (b) show the calibration curves using this calibration block with EDM notches of depths 0.05, 0.10, 0.15, 0.20, 0.25, 0.30 and 0.35 mm. Fig. 11 (a) shows the calibration curves for 64 kHz frequency whereas Fig. 11 (b) shows that for 128 kHz. Good correlation was obtained between depth of the EDM notches and eddy current response (X-axis deflection, in units). These calibrations curves were used for measuring crack depth in High Speed Steel rolls.

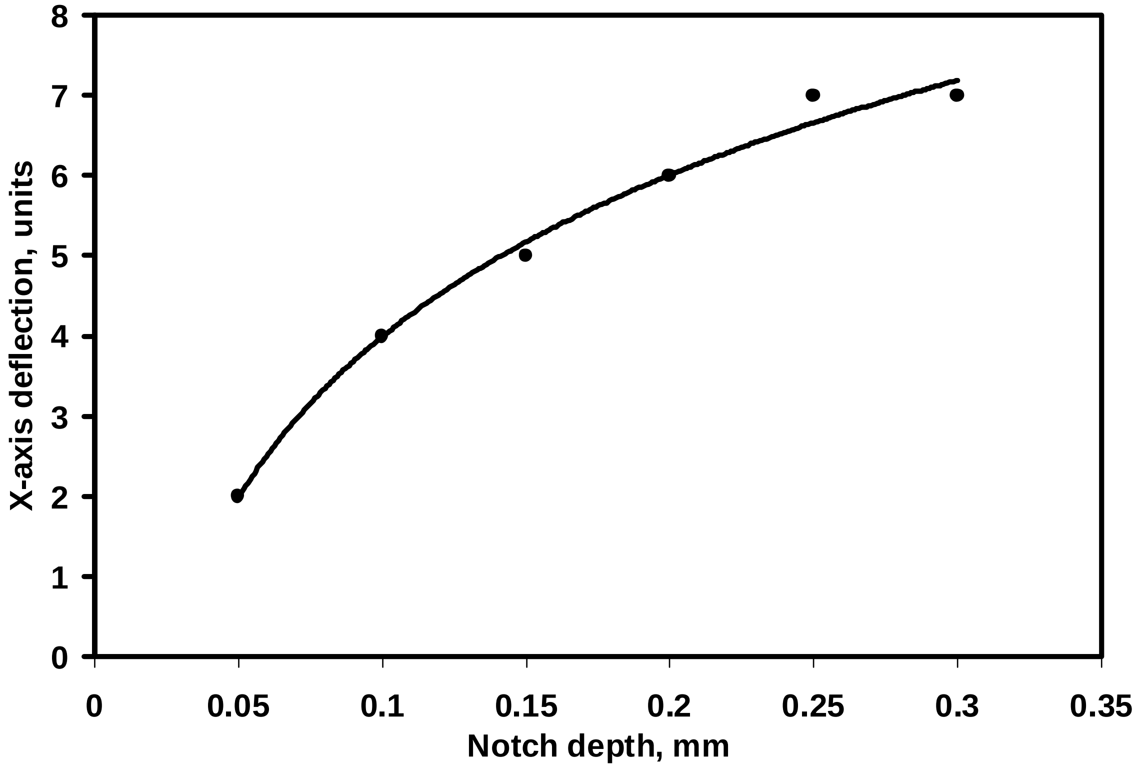

Fig. 11 (a): **Calibration curve and empirical equation to measure crack depth in High Speed Steel at 64 kHz frequency in Eddy Current testing.**

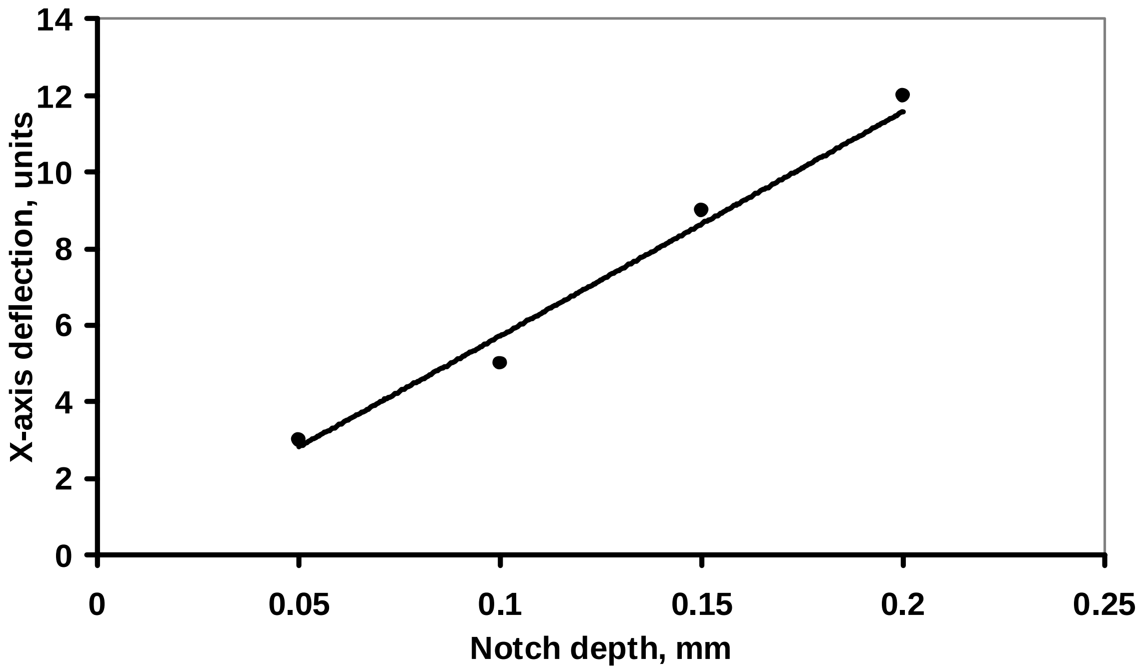

Fig. 11 (b) : **Calibration curve and empirical equation to measure crack depth in High Speed Steel at 128 kHz frequency in Eddy Current testing.**

2.3.3. Measurements on High Speed Steel Rolls under trial in the finishing stand F2:

The eddy current test results for High Speed Steel rolls have been shown in Table 3.

Table 3 : Eddy current test results of High Speed Steel Rolls of Hot Strip Mill

Roll #	Roll diameter, mm	Maximum crack depth, mm	Remarks
1457	714. 18	0. 10	Crack was eliminated by grinding
1458	714. 13	0. 10	Crack was eliminated by grinding
1441	714. 43	> 0.15	Eddy current did not inform the depth of crack. Ultrasonic 700 angle probe could measure the crack depth 3.4 mm which was eliminated by turning and grinding.

For HSS roll nos. 1457 and 1458, maximum crack depth measured was 0.10 mm which was easily eliminated by grinding. However, the crack depth in roll no. 1441 was found to be > 0. 15 mm which could not be measured by eddy current. Using 70° angle probe, in ultrasonic testing it could be measured and found to be 3.4 mm which was removed by roll turning and grinding.

3.0 PERFORMANCE OF ROLLS AND NDT

Non Destructive Evaluation (NDE) plays an important role in detecting and measuring the flaws in rolls to improve the mills performance. The implementation of ultrasonic and eddy current inspection at the Roll Shop of Hot Strip Mill resulted in reduction of roll failures in Hot Strip Mill.

Comparison of roll failure data for the period 1993-1997 (4 years) with that for the period 1997-2001 (4 years) after implementation of NDT techniques on the Roll Shop of HSM shows that roll failure was reduced from 31 rolls to 20 rolls and thus 11 rolls were saved from the failure in the mill as shown in Fig. 12.

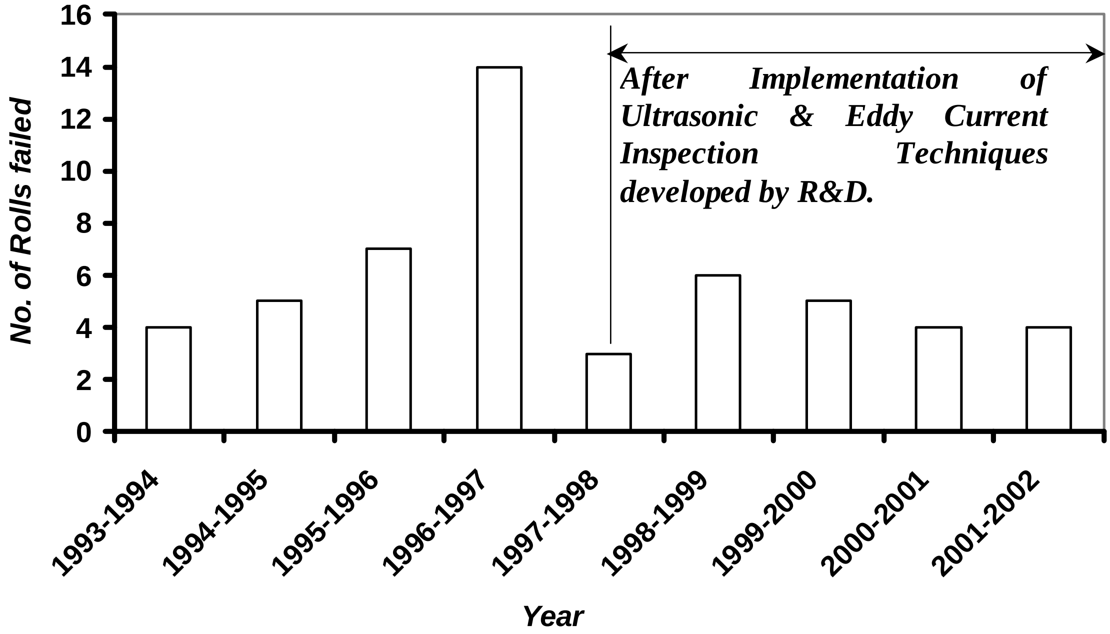

Fig. 12 : Failure of Double Poured rolls at Hot Strip Mill During 1993 to 2002.

The savings due to implementation of Ultrasonic and Eddy Current Technique at HSM Roll Shop are as given below :

- Mills down time cost due to failure of roll in the mill is approximately Rs. 10 lakhs. Hence there is saving in mill down time cost Rs. 110 lakhs for the period of 4 years or Rs. 25 lakhs per year.
- Assuming 50 % life achieved by the failed rolls and cost of each roll being approx. Rs. 8 lakhs, there is saving in roll material Rs 44 lakhs for the period 4 years or Rs. 11 lakhs per year.
- Besides savings in mills down time cost and roll materials cost other benefits (not quantified) were reduction in strip rejection due to roll failure, savings in man and machine hour costs etc.

4.0 CONCLUSIONS

The NDT techniques were developed to assess :

- Shell / core bond quality in centrifugally cast double poured rolls of finishing stand of Hot Strip Mill by ultrasonic method using normal beam probe.
- Surface cracks in Double poured rolls up to 0.7 mm depth using ultrasonic surface wave probes and 1.74 to 5.00 mm using 80°, 70° and 60° angle probes. For angularly oriented cracks, normal probes have also been used.
- Surface cracks using eddy current in High Speed Steel rolls under trial in finishing stand F2. Calibrations have been made for crack depths up to 0.25 mm.

Implementation of these NDT techniques resulted in considerable savings in mills down time cost, roll materials cost and man and machine hours cost.

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