Detection of Defects on Cold Rolling Mill (CRM) Rolls with Ultrasonic & Eddy Current Flaw Detectors

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ABSTRACT

The service induced defects in CRM rolls, due to them being subjected to complex mechanical and thermal stresses in cold rolling of steel strips or coils, if not removed completely during roll grinding, become primarily responsible for roll spalling. The high instances of roll spalling lead to increased specific roll consumption and production delays. The inspection of some 15-20% of CRM work rolls with portable Ultrasonic & Eddy Current flaw detectors was undertaken to detect and remove the service induced defects on surface and sub-surface regions of rolls which would otherwise have remained undetected leading to roll spalling and other associated failures. The incidences of spalling has reduced by up to 38% during the period of roll inspection compared to the spalling incidences in the prior periods of time leading to prolonged uses of rolls. Although no reduction in Specific Roll Consumption (SRC) has been observed, the loss of useful roll materials due to reduced incidences of spalling has reduced. The reduced occurrences of roll spalling have also resulted in savings of premature roll changing time leading to increased mill availability.

Introduction

The work and back-up rolls in 4-high Cold Rolling Mill (CRM) are subjected to arduous service conditions. The complex nature of stresses that are generated on the surface and sub-surface regions of rolls are depicted in Figure 1 [1].

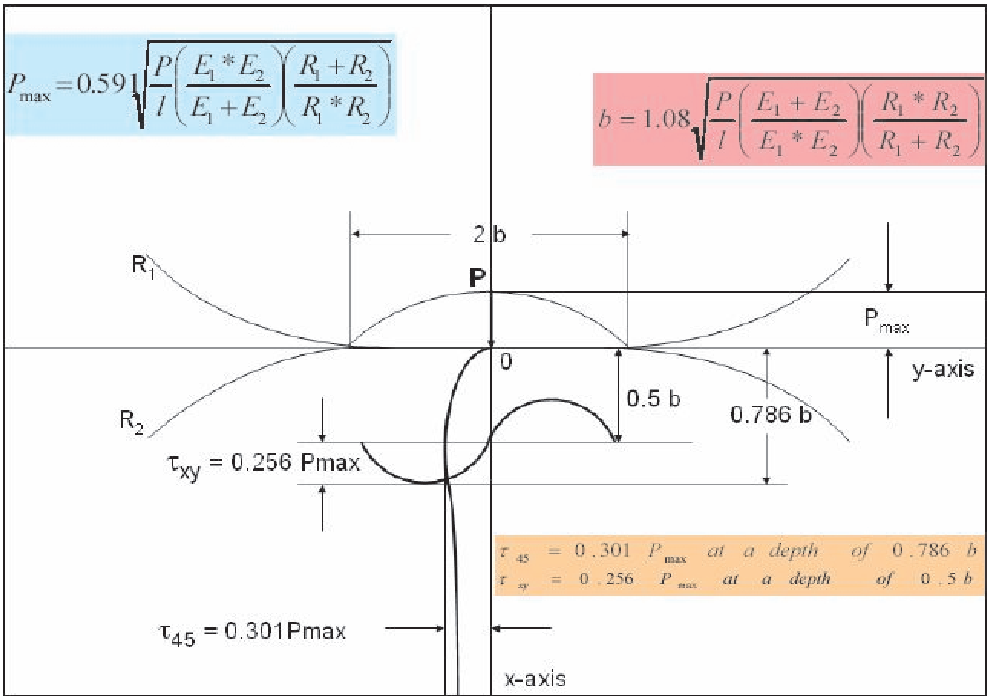

Fig. 1: Schematic representation of stresses on 4-high hot strip mill rolls [1]

The stresses present on the surface and sub-surface regions of the rolls are defined in terms of the maximum occurring contact stress, Pmax suggested by Hertz. The Hertzian contact pressure is expressed by the following equation:

$$P_{max} = 0.591\sqrt{\frac{P}{l}\left(\frac{E_1 * E_2}{E_1 + E_2}\right)\left(\frac{R_1 + R_2}{R_1 * R_2}\right)}$$

P = Rolling load
l = Length of contact between work and back-up rolls
E_1 & E_2 = Young's Modulus for work and back-up rolls
R_1 & R_2 = Radii of work and backup rolls

The stresses generated on the surface in radial (σ_x), tangential (σ_y) and longitudinal (σ_z) directions become maximum on surface with a magnitude of $\sigma_x = \sigma_y = 1.0P_{max}$ and $\sigma z = 0.6P_{max}$.

According to the Hertz theory, the pressure on the contacting surfaces is in elliptical distribution. If 2b is the width of elliptical contact resulting from elastic deformation, then b can be expressed as follows:

$$b = 1.08\sqrt{\frac{P}{l}\left(\frac{E_1 + E_2}{E_1 * E_2}\right)\left(\frac{R_1 * R_2}{R_1 + R_2}\right)}$$

The stresses generated in the sub-surface regions are also defined in terms of P_{max}. The shearing stresses on a plane inclined to 45º to the x-y plane (ι45) and on a plane parallel to x-y plane (ι45) are of special significance since these stresses correspond to the highest mean stress and stress amplitude respectively. Since the fatigue intensity of a material is a function of both the stress magnitude and stress amplitude, these stresses need to be examined while studying the rolling contact fatigue behaviour of a material. These shearing stresses are expressed by the following equations:

$$\tau_{45} = 0.301 P_{\max} \textit{ at a depth of } 0.786b$$

$$\tau_{xy} = 0.256 P_{\max} \textit{ at a depth of } 0.5b$$

The work rolls and back-up rolls are subjected Rolling Contact Fatigue (RCF), wear and friction, and as a result fatigue and thermal cracks appear on the surface and sub-surface regions of the rolls. The cracks on the work and back-up rolls are oriented in random directions because of the complex stresses present on the surface and sub-surface regions of the rolls. The typical crack geometries present on the surface of rolls and their propagation paths along the sub-surface regions are presented in Figure 2.

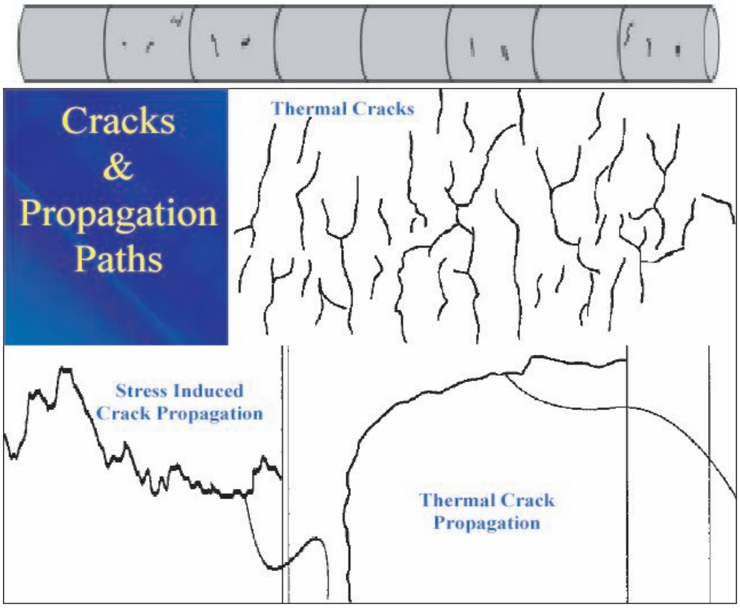

Fig. 2: Typical crack geometries & propagation path

In absence of Non Destructive Testing (NDT) of these rolls, it is almost impossible to detect and remove the cracks that are generated on the surface and sub-surface regions of the rolls. These cracks, when present on the rolls, may lead to in-service or catastrophic failures. The in-service or catastrophic roll failures not only lead to loss of useful roll diameter but also result in mill production delays [2].

The inspection of rolls with NDT systems requires the use of an optimum combination of different techniques, devices, and an adequate expertise level in order to correctly interpret the test results and converting those to practical significances. Though the ideal solution for inspection of steel mill rolls is application of on-line automated state-of-the-art NDT systems, the roll inspection with portable NDT system may serve as a cost effective solution when used in a suitable manner employing the correct techniques and skill [3,4].

The present work has been aimed at introducing the portable Ultrasonic and Eddy Current systems for inspection of CRM Rolls in order to detect the roll defects accurately and remove them before further use in the mill so as to minimize the occurrences of roll spalling due to such contributing factors.

Experiments

The roll inspection with portable Ultrasonic and Eddy Current flaw detectors was carried out for a period of one year starting from April 2010 till March 2011. Some 225-250 rolls of CRM-I&II combined were inspected per month amounting to 15-20% of the rolls in circulation. The outcome of the inspection is discussed in the Results and Discussion section. A brief discussion on the principles of Ultrasonic and Eddy Current testing techniques followed by elaboration of the inspection methodology employed under the current program follows herewith for a general understanding of the advantages and limitations of the NDT testing techniques and visualizing the need for future augmentations of the testing services.

Principles of ultrasonic testing (UT)

Ultrasonic Testing (UT) uses high frequency sound energy to conduct examinations and make measurements. Ultrasonic inspection can be used for flaw detection/evaluation, dimensional measurements, material characterization, and more. As illustrated in Figure 3, the typical UT inspection system consists of several functional units, such as the pulser/receiver, transducer, and display devices.

A pulser/receiver is an electronic device that can produce high voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen. In the applet below, the reflected signal strength is displayed versus the time from signal generation to when an echo was received. Signal travel time can be directly related to the distance that the signal traveled. From the signal, information about the reflector location, size, orientation and other features can sometimes be gained [5,6].

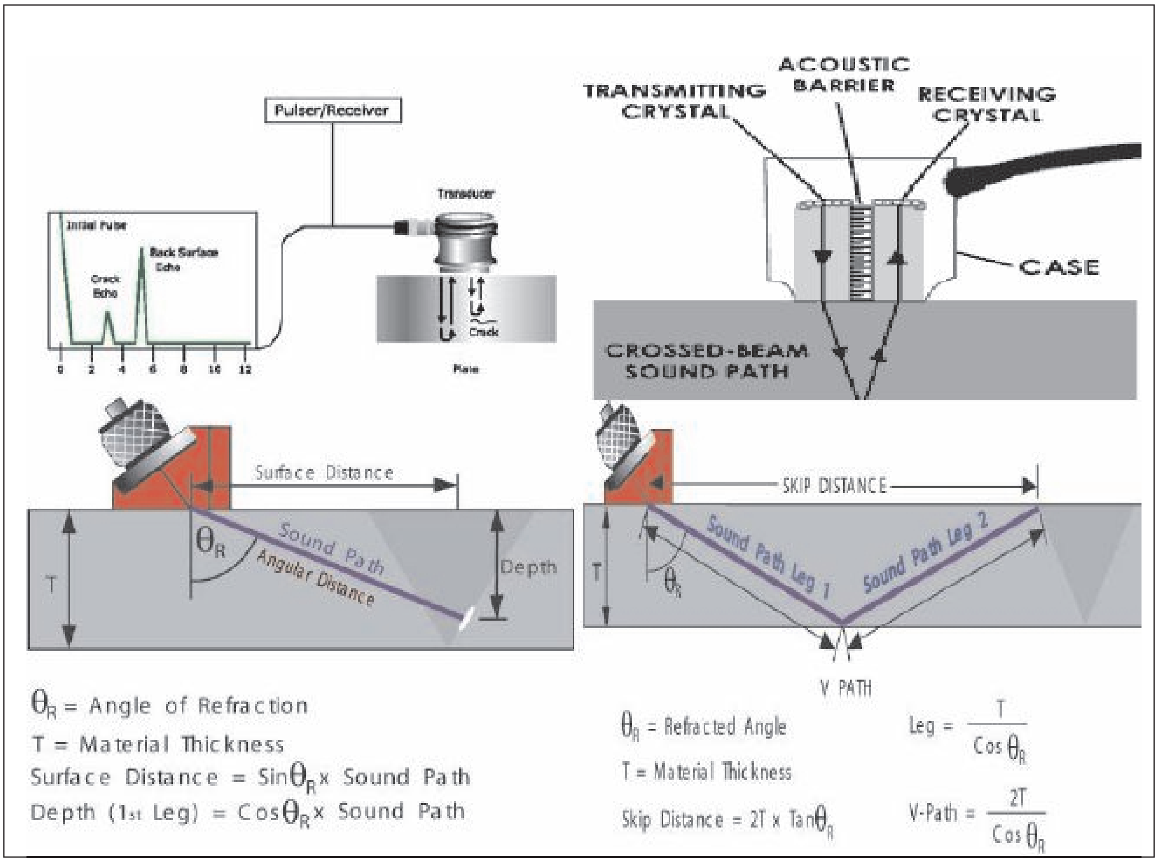

Fig. 3: Principles of Ultrasonic Testing

Principles of Eddy Current (EC) Examination

Eddy current inspection is one of several NDT methods that use the principal of electromagnetism as the basis for conducting examinations. Several other methods such as Remote Field Testing (RFT), Flux Leakage and Barkhausen Noise Analysis also use this principle. The basic operations involved in the eddy current examination are depicted in Figure 4.

Eddy currents are created through a process called electromagnetic induction. When alternating current is applied to the conductor, such as copper wire, a magnetic field develops in and around the conductor. This magnetic field expands as the alternating current rises to maximum and collapses as the current is reduced to zero. If another electrical conductor is brought into the close proximity to this changing magnetic field, current will be induced in this second conductor. Eddy currents are induced electrical currents that flow in a circular path. Defects such as cracks are detected when they disrupt the path of eddy currents and weaken their strength[7-10].

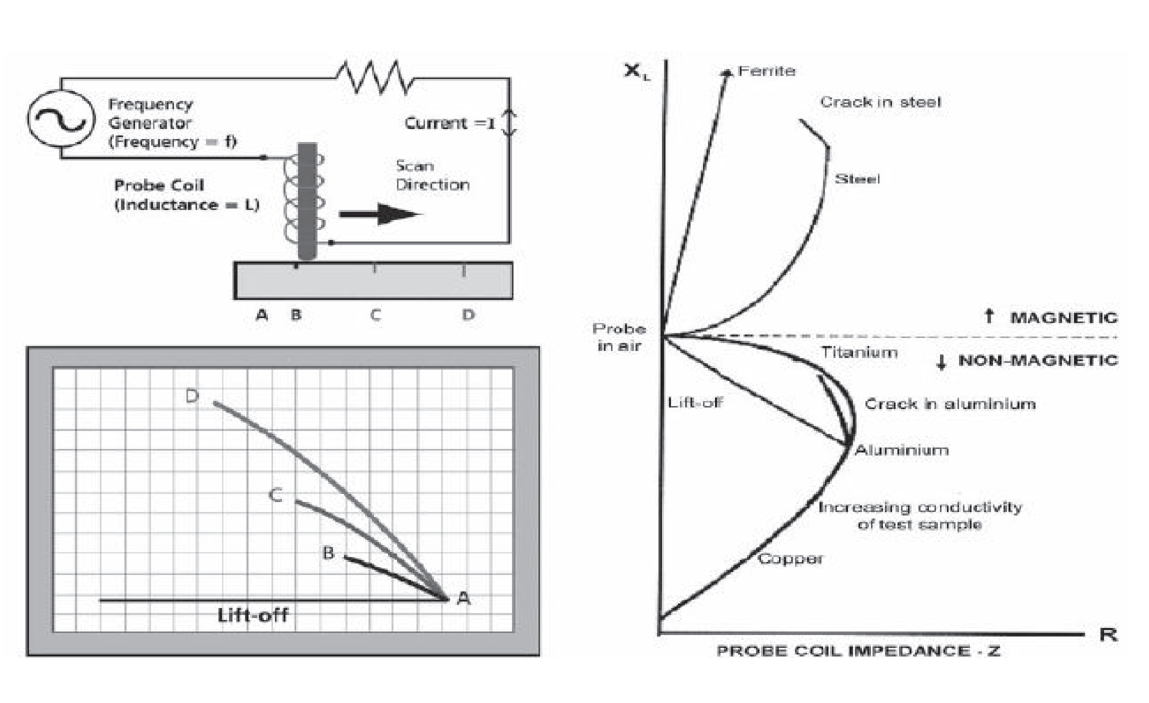

Fig. 4: Principles of Eddy Current Examination

Methodology of Roll Inspection

The EC surface probes are used for inspection of work rolls to detect the presence of surface breaking cracks, and stock removal is decided accordingly. The work rolls, after being removed from the mill are loaded on the grinding machine and the worn out layer is removed first. The probes are mounted in a probe holder, which is moved along the longitudinal axis of the rolls starting from one end of the roll while the roll is rotated around its axis on the grinding machine. The speed of movement of probe holder and the rotational speed of the rolls are synchronized in a manner so as to cover the full volume of the roll to the extent possible with the manual operations. The signals from the presence or absence of defects are analyzed and the stock removal is decided accordingly. The rolls are inspected after the stock removal once again in the manner stated, in order to ensure the defect free rolls for the subsequent campaign in the mill.

The work rolls are further inspected with the UT after in order to assess sub-surface defects so as to enable a judgment on the further use of rolls in the mill. A combination of The TR (Transmitter-Receiver) probe or normal beam probe, angle beam probes (30/45/70º) and/or surface wave (90º) is used and the inspection is performed in the same manner as that in the case of EC inspection. The schematic representation of the inspection methodology is presented in Figure 5.

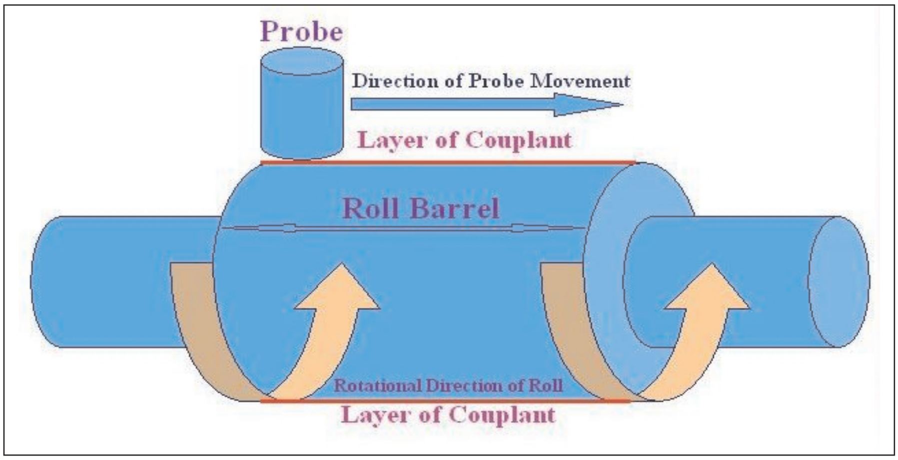

Fig. 5: Schematic Representation of Roll Inspection Methodology

Results and Discussions

The data on roll spalling in CRM-I&II for a period of 1st six months (Apr.-Sept.'2010) and 2nd six months (Oct.'2010-Mar.'2011), during which the roll inspection was introduced, alongside the data for a period of six months (Oct.'2009-Mar.'2010) prior to introduction of roll inspection, is presented in Table 1.

Table 1: Roll Spalling in CRM-I&II - before (without) & after (with) introduction of UT & ECT

Mill	Parameter	Data for 6 months		
		For period before (without) roll inspection through Ultrasonic & Eddy Current Testing (Oct.'09-Mar.'10)	For period after (with) roll inspection through Ultrasonic & Eddy Current Testing (Apr.'10-Sept.'10)	For period after (with) roll inspection through Ultrasonic & Eddy Current Testing (Oct.'10-Mar.'11)
Tandem Mill - I	No. of roll spalls	65	46	33
Tandem Mill - II	No. of roll spalls	25	19	23
Total		90	65	56

It is evident that the occurrences of roll spalling after introduction of roll inspection with UT & ECT is reduced from 65 to 46 in TM-I and from 25 to 19 in TM-II. Thus, in totality, the incidences of roll spalling in TM-I&II has reduced from 90 to 65, corresponding to a percentage reduction of about 28%. In the following six months, i.e. during Oct.'2010-Mar.'2011, the incidences of roll spalling has been 33 nos. in TM-I and 23 nos. in TM-II, totaling to 56 nos.. Thus, during Oct.'2010-Mar.'2011, the cases of spalling have further reduced incrementally by about 14% compared to the previous 6 months period, i.e. Apr.'2010-Sept.'2010. With the figures, it is evident of the fact that the reduction in spalling in the 2nd six months of the trial period, i.e. during Oct.'2010-Mar.'2011, is about 38% compared to the base period, i.e. Oct.'2009-Mar.'2010, when UT & ECT was not introduced.

In order to understand the defect distribution pattern, the frequency distribution of different extent of defects has also been plotted (Figure 6) as percent of the total observed occurrences of defects.

As can be seen in Figure 6, though the extent of defects ranges from 0.2 mm deep to 2.5 mm deep, the defects in the range of 0.2 mm to 0.8 mm account for the majority of the cases (~80%).

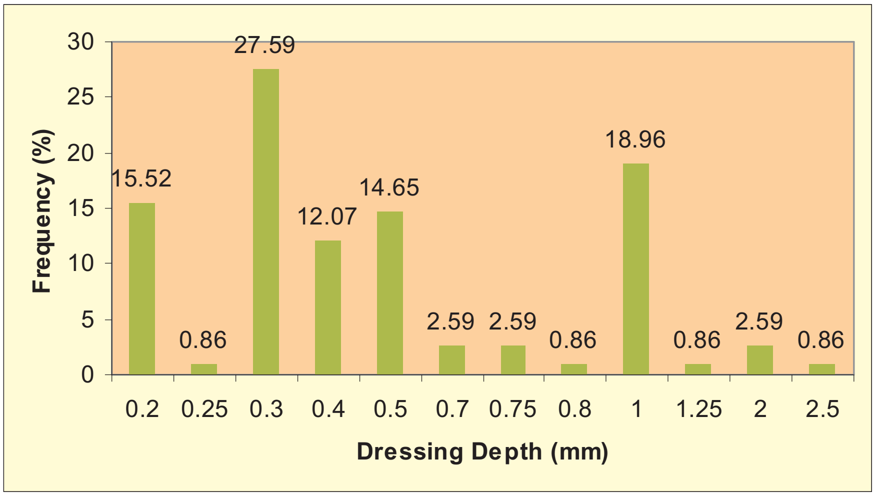

Fig. 6: Frequency Distribution of Defect Depth

Further, it is observed that out of these 80% cases, the defects in the range of 0.2 mm to 0.5 mm accounts for 90% of the cases and the rest 10% of the cases represents the defects in the range of 0.5 mm to 0.8 mm.

The Roll Shops in a cold tandem steel mill nominally removes 0.5 mm stock between the roll campaigns in absence of inspection with Ultrasonic & Eddy Current devices. The stock removal may even sometimes be as low as 0.3 mm where the mill professionals are confident of strict control over mill parameters. However, in cases when the defects were induced beyond the established practice of stock removal, there remains a threat of in-service roll failures in subsequent campaigns since the left out defects will always get accumulated and propagated resulting in roll failures. It is therefore required to tradeoff between the roll consumption and roll failures. On the one hand, stock removal beyond the established norms, based on the observations of UT & EC inspection, a temporary increase in roll consumption will be observed. On the other, if the stock removal is based on norms, with a probability of having the service induced defects left, the rolls will be more prone to failures leading to loss of useful roll diameter and increased production delays. It has been observed that the loss of useful diameter on account of roll spalling is reduced by 2.5-3% even though there is no reduction in Specific Roll Consumption.

It is also observed (Figure 6) that the defects sometimes (in more than 20% cases) are in the range of as high as 1.0mm to 2.5mm deep. In absence of roll inspection with Ultrasonic & Eddy Current devices, the stock removal to the extent of 2.5 mm will never be undertaken leaving a threat of in-service roll failures during further uses of the rolls.

This has been validated by the observation that the likelihood of roll failure in case of untested rolls is 2.5-3 times more than that in case of the tested ones.

It is therefore a necessity to accurately determining the extent of defects induced during service of rolls in the mill and to perform grinding accordingly to reduce the occurrences of in-service roll failures.

It may however seem from the above discussion that increased stock removal will lead to increased specific roll consumption. This may be true if the data of specific roll consumption is looked into over a small period of time, say 6-12 months. This will be further prominent if only a small proportion, say 15-20%, of the rolls in circulation is being inspected. As long as the instances of in-service roll failures keep on decreasing, the slight increase in specific roll consumption is not a major concern. However, if the increase in specific roll consumption is more alarming, the other reasons for roll failures (e.g. excessive campaign length, inferior quality of roll and input material, inadequate cooling and lubrication, mill accidents etc.) need to be analyzed and arrested. Once an optimum trade off between specific roll consumption and in-service roll failures is established during an extended period of time, say 18-24 months covering inspection of 100% of rolls in circulation, the decrease in specific roll consumption shall be observed along with decrease in instances of in-service roll failures.

Nevertheless, it is suggested that the grinding is performed in strict adherence to the observations of Ultrasonic and Eddy Current inspection. Besides, the other probable reasons for excessive roll failures, i.e. due to metal pick-up, fire-cracks, improper roll cooling, roll bite lubrication problem etc., must also be looked into to realize reduction in specific roll consumption and production delays.

Conclusion

Since the roll spalling may be primarily attributed to inherent roll defects and defects induced in the rolls through various mill operational aspects, application of techniques for early detection of inherent and induced invisible surface defects and sub-surface defects and elimination of these defects during the process of roll grinding, before sending the rolls to the mills serves as an important aid towards reducing the incidences of roll spalling. It is envisaged that the benefits in terms of reduction in incidences of spalling, the resultant saving in loss of useful roll material and production delays due to premature roll changing may be achieved to a larger extent with the introduction of inspection of 100% of the rolls under circulation in CRM-I and CRM-II with Ultrasonic & Eddy Current systems.

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