Application of Ultrasonic and Eddy Current Testing for Inspection of Rolls

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Abstract. The work rolls used for hot and cold rolling of steel strips are subjected to severe mechanical and thermal stresses resulting in rolling contact fatigue, wear and plastic deformation on the roll bodies. The arduous service condition often leads to generation of thermal and mechanical cracks on roll surfaces and may vary from micro to macro levels in the form of discrete or continuous networks. These service induced cracks are required to be completely removed by roll grinding taken up in between service campaigns. However, in absence of Non Destructive Testing (NDT) of rolls, it is almost impossible to detect and remove any surface or sub-surface crack which may be generated during rolling. The cracks which remain undetected eventually propagate and join each other to cause fracture of the roll surfaces, leading to spalling or catastrophic failures in subsequent service campaigns. The roll failure not only brings about loss of costly roll materials but also results in severe loss of mill productivity as well.

With a view to reduce the incidences of in-service roll failures, a program was initiated by RDCIS to carry out roll inspection with a unique combination of portable Ultrasonic and Eddy Current flaw detectors. A proper understanding of the nature and extent of the service induced cracks coupled with the use of suitable methodology was exploited to produce results which were suitably interpreted and converted to that of practical significance. Appropriate selection of probes and frequencies for Ultrasonic and Eddy Current inspection with their application on roll surfaces to produce authentic and reproducible defect signals, roll surface preparation and implementation of a suitable inspection methodology constituted the scope of the present work.

Application of Ultrasonic and Eddy Current method of inspection of work rolls in Hot Strip Mill of Bokaro Steel Plant resulted in reduction of roll spalling by ~55% as compared to the incidences of roll spalling during the periods without NDT assisted roll grinding. The instances of roll spalling in Cold Rolling Mill of Bokaro Steel Plant was also reduced by ~22% with NDT assisted roll grinding as compared to the occurrences of roll spalling during the period when roll inspection with Ultrasonic and Eddy Current was not available to shop.

Introduction

The work and back-up rolls in 4-high Hot Strip Mill (HSM) and Cold Rolling Mill (CRM) are subjected to rolling contact fatigue, wear, work hardening and thermal shocks due to complex nature of stresses that are present during cold rolling of steel strips and coils leading to generation of cracks and other associated defects on surface and sub-surface regions of rolls which propagate and join each other leading to removal of a chunk of material from the roll body termed as spalling. The typical thermal and fatigue (mechanical) cracks and there propagation path and the resultant spalling surface are shown in Figure 1 and Figure 2 respectively.
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 [1,2,3].

The inspection of rolls with NDT systems require using an optimum combination of different techniques, devices and 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 [4,5,6,7]. Table 1 lists some of the advantages and limitations of several available NDT techniques that can serve as a ready reference for selection of appropriate techniques for the specific inspection job [8].
Table 1. Advantages & Limitations of different NDT methods

<table>
<thead>
<tr>
<th>Defects</th>
<th>Inspection Methods</th>
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<tr>
<td></td>
<td>UT</td>
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<tr>
<td>Radial Depth</td>
<td>Surface Probe – 1.25 mm</td>
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<td></td>
<td>Dual Probe – 0 to 150 mm</td>
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<td></td>
<td>Normal Beam Probe – 12.5 mm to Bore</td>
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<td></td>
<td>0.1-0.2 mm</td>
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<tr>
<td>Surface Micro Cracks (&lt;0.15 mm)</td>
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<tr>
<td>Surface Macro Cracks (&gt;0.15 mm)</td>
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<td>Sub-surface Cracks</td>
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<td>Residual Stresses</td>
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<td>Metallurgical Changes</td>
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<td>Sensitivity to Residual Magnetism</td>
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[UT: Ultrasonic Testing; EMAT: Electro-Magnetic Acoustic Transducer; EC: Eddy Current; LPI: Liquid Penetrant Inspection; MPI: Magnetic Particle Inspection; BNA: Barkhausen Noise Analysis]

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

Experimental

The inspection of rolls was carried out with portable hand-held ultrasonic and eddy current devices covering about 225-250 number of rolls in a month for a period of 6 years (2007-08 to 20012-13) and 2 years (2010-11 & 2012-13) in hot strip mill and cold rolling mill respectively. A proper understanding of the nature and extent of the service induced cracks coupled with the use of suitable methodology was exploited to produce results which were suitably interpreted and converted to that of practical significance. Appropriate selection of probes and frequencies for Ultrasonic and Eddy Current inspection with their application on roll surfaces to produce authentic and reproducible defect signals, roll surface preparation and implementation of a suitable inspection methodology constituted the scope of the present work.

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 illustrate
in Figure 3, the typical UT inspection system consists of several functional units, such as the pulser/receiver, transducer, and display devices.

![Figure 3. Principles of Ultrasonic Testing](image)

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 figure above, 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 location, size, orientation of the defects and other features can be gained. Working on the same principle, a combination of normal beam, transmit-receive, angle and surface wave probes might be required to detect the defects oriented in either of the directions at depths ranging from surface to through thickness of the body to be inspected.

**Principles of Eddy Current Testing (ECT).** 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. A combination of probes of varying frequencies may be required for detecting micro and macro defects residing on the surface and near-surface regions of the body to be inspected. It is the sizes and locations of these defects that determine the probe frequency.

**Methodology of Roll Inspection.** The Eddy Current (EC) surface probes were used for inspection of work rolls to detect the presence of surface breaking cracks and stock removal was decided accordingly. The work rolls, after being removed from the mill were loaded on the grinding machine and the worn out layer was removed first. The probes were mounted in a probe holder, which was moved along the longitudinal axis of the rolls starting from one end of the roll while the roll was rotated around its axis on the grinding machine. The speed of movement of probe holder and the rotational speed of the rolls were 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 were analyzed and the stock removal was decided accordingly. The rolls were 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 were further inspected with the Ultrasonic Testing (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 Transmitter Receiver (TR) probe or normal beam probe, angle beam probes (30/45/70°) and/or surface wave (90°) was used and the inspection was 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.

Figure 5. Schematic Representation of Roll Inspection Methodology

Results and Discussions

The incidences of roll spalling in Hot Strip Mill (HSM) of Bokaro Steel Plant are presented in Figure 6. It can be observed that the incidences of work roll spalling have always been much less upon application of roll inspection with ultrasonic and eddy current systems (2007-08 to 2012-13) compared to that before the introduction of roll inspection system (2006-07). During the periods of roll inspection, the reduction in work roll spalling is to the extent of 68% in 2012-13 (20 numbers of work roll spalling in 2012-13 compared to 63 numbers of work roll spalling in 2006-07). However, the reduction in work roll spalling is also observed to a lesser extent of 40% in 2010-11 (38 numbers of work roll spalling in 2010-11 compared to 63 numbers of work roll spalling in 2006-07).

Similarly, the incidences of back-up roll spalling have also reduced by 54% in 2007-08 (59 numbers of back-up roll spalling) and by 61% in 2008-09 (49 numbers of back-up roll spalling) compared to that in 2006-07 (127 numbers of back-up roll spalling). The incidence of back-up roll spalling during the period from 2009-10 to 2012-13 is not being reported here because the Hot Strip Mill (HSM) of Bokaro Steel Plant has started using superior quality of back-up rolls which are not as prone to spalling. Nevertheless, back-up rolls are inspected whenever felt necessary. However, there is hardly any instance of back-up roll spalling in Hot Strip Mill of Bokaro Steel Plant.

The variation in reduction in roll spalling in Hot Strip Mill is on account of two reasons. Firstly, the numbers of rolls inspected during different periods are not similar. Secondly, roll spalling is not only originated from service induced defects but also due to other reasons. Nevertheless, a decreasing trend in roll spalling is certainly observed.
As can be observed from the Figure 7, the incidences of work roll spalling in Cold Rolling Mill (CRM) of Bokaro Steel Plant has reduced by 11% upon inspection of work rolls with ultrasonic and eddy current systems in 2010-11 (117 numbers of work roll spalling in 2010-11 compared to 131 numbers of roll spalling in 2009-10). Further, a reduction in work roll spalling by 34% is observed in 2012-13 (101 numbers of work roll spalling in 2012-13 while the rolls were inspected with ultrasonic and eddy current systems compared to 153 numbers of work roll spalling in 2011-12 when the roll inspection was not employed). The back-up rolls of Hot Strip Mill and Cold Rolling Mill of Bokaro Steel Plant are used interchangeably and spalling of back-up rolls in Cold Rolling Mill was not a matter of concern during the periods of roll inspection and hence not being reported here. Nevertheless, back-up rolls are inspected whenever felt necessary. However, there is hardly any instance of back-up roll spalling.

The variation in reduction in work roll spalling in Cold Rolling Mill in the range of 11-34% is due to large difference in the numbers of rolls inspected during 2010-11 (only 15-20% of the work rolls in circulation were inspected) and 2012-13 (almost 100% of the work rolls in circulation were inspected). It can be noted that inspite of inspection of 100% of the work rolls in circulation the incidences of spalling has not been eliminated completely. This is attributable to spalling originating from other sources [9,10].
Conclusions

Roll spalling is 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 and sub-surface defects and their elimination during roll grinding, before sending the rolls to the mills, serves as an important aid towards reducing the incidences of roll spalling. Introduction of ultrasonic and eddy current roll inspection system has exhibited benefits in terms of reduction in incidences of spalling, the resultant saving in loss of useful roll material and production delays to premature roll changing. It is therefore recommended to inspect 100% of the rolls under circulation in the CRM using the NDT techniques.

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